DETAILED STUDIES OF

FROST ACTION IN SOILS

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DETAILED STUDIES OF
FROST ACTION IN SOILS

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ABSTRACT

A well graded silt was subjected to frost heave tests. Specimens three inches in diameter by nine, sixteen and twenty four inches long were frozen from the top down, using the "open system" of test. Instrumentation was provided for the determination of heave, and both piezometric pressure and temperature at intervals along the specimens. Pressures were determined by means of water-over-mercury manometers connected to porous tapping points embedded in the speciments.

The variation in the piezometric pressure along the flow path was found to be incompatible with Darcy's law for the flow of water through a saturated homogeneous material. The difference was not reconciled by the consideration of variations in viscosity and void ratio along the flow path.

Assuming that there was continuity of flow between the reservoir and the frost line, the permeability of the silt was found to decrease with increasing negative piezometric pressures, from zero throughout the pressure range recorded. This could not be explained by the entry of air into the specimen as it occurred for negative pressures that were much smaller than the capillarity of the material.

The pressure-permeability relationships obtained suggested the applicability of "unsaturated" flow theory to soil moisture movements due to freezing. This possibility was supported by similarities observed in certain flow characteristics for flow produced by ice lensing, evaporation and applied negative pore pressures. Furthermore, Gardner's empirical equation for the pressure-permeability curves for flow under negative pressure was fitted to the frost heave test data although the n-value required was lower than any reported by Gardner.

ACKNOWLEDGEMENTS

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CHAPTER I

INTRODUCTION

Certain phenomena related to the freezing and thawing of soils have been observed from early times but these received little, if any, serious study prior to the advent of modern transportation systems.[1] Subsequently, "frost action"[2] has become an economic problem of prime importance to highway, airport and railroad administrations.

One field of thought concerning frost heave stemmed from the known fact that water increases in volume by about nine percent when it changes into ice. Between 1916 and 1930, Taber (1, 2, 3, 4)[3] performed tests which showed that crystals are capable of exerting pressure during growth. Furthermore, he showed that the heave obtained in his tests was often greater than that which could be explained on the basis of volume change on freezing, alone. On the basis of his findings, he suggested that the difference was due to "ice segregation" which would occur when there was migration of moisture to the frost line. This hypothesis was substantiated when heave occurred with a pore liquid which contracted on freezing. Thus, the importance of the availability of water was recognized and the

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[1]For a survey of past work in the field of frost action and related fields, see "Frost Action in Roads and Airfields - A Review of the Literature 1765-1951", A.W. Johnson, Highway Research Board, Special Report No. 1, 1952.

[2]The frost action terminology used is in accordance with the list of terms and definitions approved by the Highway Research Board Committee on Frost Heave and Frost Action in Soils(5). Other specialized terms will be explained as they occur.

[3]Numbers in parentheses refer to the bibliographical listings.

possibilities for controlling frost heave were extended to the control of soil moisture movements.

It was recognized by Taber, that the availability of water at the frost line is dependent on the existence of a source of supply within reach of the capillary rise of the material, and on the resistance offered by the material to flow from the source to the frost line. The first of these factors may be controlled in laboratory tests and therefore, the "open" and "closed" system concepts of Taber must be considered when comparing frost heave test results from independent sources.

Based on both field and laboratory investigations Taber (4), Beskow(6)[1], and Casagrande(7) each suggested certain grading limits for frost susceptible material. The Casagrande criterion, which is commonly used on this continent, has very limited value for borderline materials such as dirty gravels. According to Ducker(8)[1], "The quantitative frost behavior of a soil is determined not by the percentage of grain sizes below 0.02 mm., but by the mineralogical and chemical composition of the 'binding' material".

Beskow(6) performed frost heave tests on both natural soils and separated fractions. These showed that the maximum heave occurred for grain sizes in the fine silt range (using M.I.T. grain size scale). On the basis of investigations into the effect of both surcharge and applied pore stresses of different magnitudes, Beskow concluded that "Capillary and load pressures then have a similar effect and the

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[1]Reference is to the translation.

frost heave can be stated in relation to the total pressure acting at the frost line, which is the sum of the two. The hypothesis used by Beskow in determining mathematical expressions relating the rate of heave to the total pressure at the frost line, was that the pressure deficiency or negative pore fluid pressure has a maximum value equal to the capillarity[1] of the material.

Both Taber(4) and Beskow(6) considered that moisture movements took place in the liquid phase, although there is controversy as to the significance of vapor diffusion in these moisture movements. By computing the rate at which moisture could be moved by vapor diffusion, using the equations given by Zunker, and comparing with the rates of flow obtained in frost heave tests, Beskow(6) showed that vapor diffusion could account for only about one thousandth of the rate of heave obtained. More recently, Kuzmak and Serda(9), on the basis of studies of moisture movements in porous media, concluded that water movements due to suction gradients take place in the liquid phase.

The effect of different admixtures was investigated by Yurkiw(10), Luck(11), and Lambe(12). Yurkiw showed that lignosol was effective in reducing heave, and that it reduced the permeability of the specimens. He suggested that the reduction in permeability was due to reduced pore space. Luck concluded that "The viscosity of the saturating fluid is a contributing factor, but not a controlling factor, in the reduction of frost heaving of soils". Lambe reported on a testing program in which a variety of additives and soil types were used. These additives were grouped into the following classifications; void pluggers and cements, aggregants, dispersants, and waterproofers.

[1]The negative pressure required to draw air through an initially saturated sample.

These tests showed the polyvalent cations and the dispersants to be the most promising in reducing heave, while "dirty" gravels, sandy clays, and silty sands were the most responsive to treatment. Uniform silts and lean clays were the least responsive.

Ruckli(13) and Jumikis(14) gave a theoretical treatment to the thermodynamical aspects of the frost heave problem. Penner(15) introduced the concepts of unsaturated flow and of moisture-tension relationships into the frost heave problem.

In the various investigations referred to above, the effect of varying the length of the flow path (water reservoir to frost line) was not tested. Also, there is a lack of data on the physical conditions that exist or develop in the pore fluid during the freezing process. This investigation is intended to provide more information in both respects.

CHAPTER II

THEORY

As mentioned previously, frost heave is due to ice segregation which takes place when moisture migrates to the frost line. Comparing the rate of moisture movement by vapor diffusion, as computed using equations given by Zunker, with the flow determined from frost heave tests, Beskow(6) concluded that movements in the vapor state are negligible. More recently, Kusmak and Sereda(9) found that moisture movements in porous material due to suction gradients took place in the liquid phase. Therefore only theory of liquid flow will be considered.

Liquid Flow in General

It is characteristic of liquids that shearing stresses produce flow. The existance of shearing stresses is dependent upon differences in the energy level. In fluid mechanics, Bernoulli's equation expresses explicitly three energy components (16, 17). An element within a mass of liquid will possess pressure energy due to the pressures acting on that element. It will have elevation or potential energy by virtue of its position with respect to any arbitrary datum, and if the element is in motion, it will have kinetic or velocity energy. Expressed algebraically,

$$E_v = V^2/2g, \quad E_p = p/\gamma_L = h, \quad \text{and} \quad E_e = z$$

where V is the velocity of the element, g is acceleration due to gravity, p is the average pressure acting on the element, γ_L is the

unit weight of the liquid, h expresses p in terms of height of liquid, and z is the distance from the element to an arbitrary datum. The total energy is equal to the sum of the three components.

$$E = z + p/\gamma_L + V^2/2g \quad = \quad z + h + V^2/2g \qquad \text{(II.1)}$$

The quantities in equation (II.1) are energies per unit weight of the liquid considered, hence the units of length. The term h is meaningful only if the liquid is incompressible. In fluid mechanics, liquids are considered to be incompressible for steady flow conditions.

Consider the flow in a uniform pipe(See Plate 1). Provided that the various energy components can be evaluated at sections 1 and 2, the energy loss per unit weight of liquid H, will be given by the equation

$$(z_1 + h_1 + V_1{}^2/2g) - (z_2 + h_2 + V_2{}^2/2g) = H$$

or

$$(z_1 - z_2) + (h_1 - h_2) + (V_1{}^2 - V_2{}^2)/2g = H \qquad \text{(II.2)}$$

where V_1 and V_2 represent average velocities, calculated by dividing the volume of flow per unit time by the cross-section area of the pipe. The subscripts designate the sections shown on Plate 1.

A plot of the type shown on Plate 2 may be obtained experimentally using equation (II.2) and data from a pipe flow apparatus. At the low end of the average velocity scale, the energy loss is proportional to the average velocity, a condition which defines laminar flow. At higher velocities the flow is referred to as turbulent. Here the energy loss is approximately proportional to the average velocity squared.

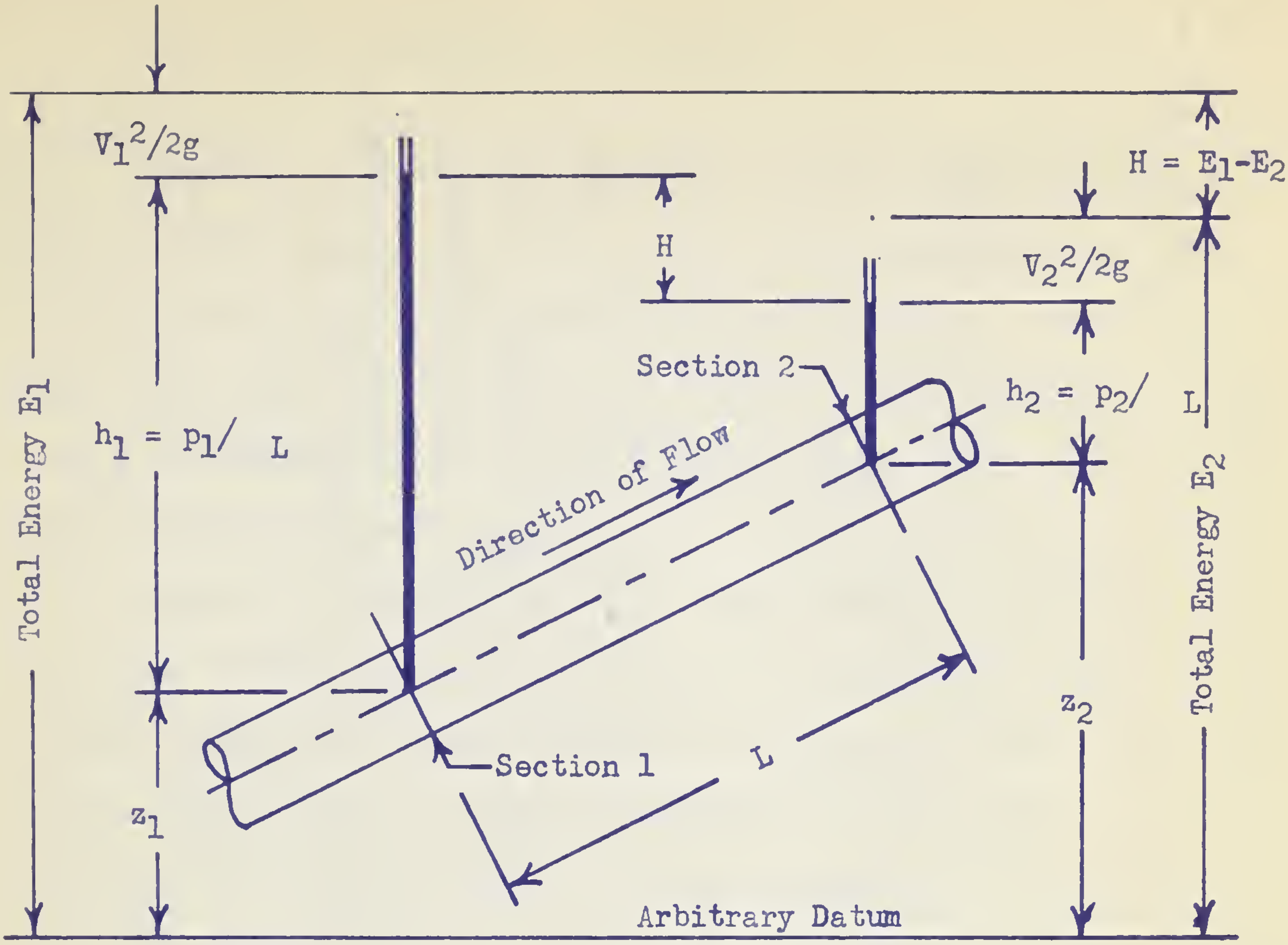


PLATE 1

ENERGY CONCEPTS APPLIED TO FLOW IN A UNIFORM PIPE

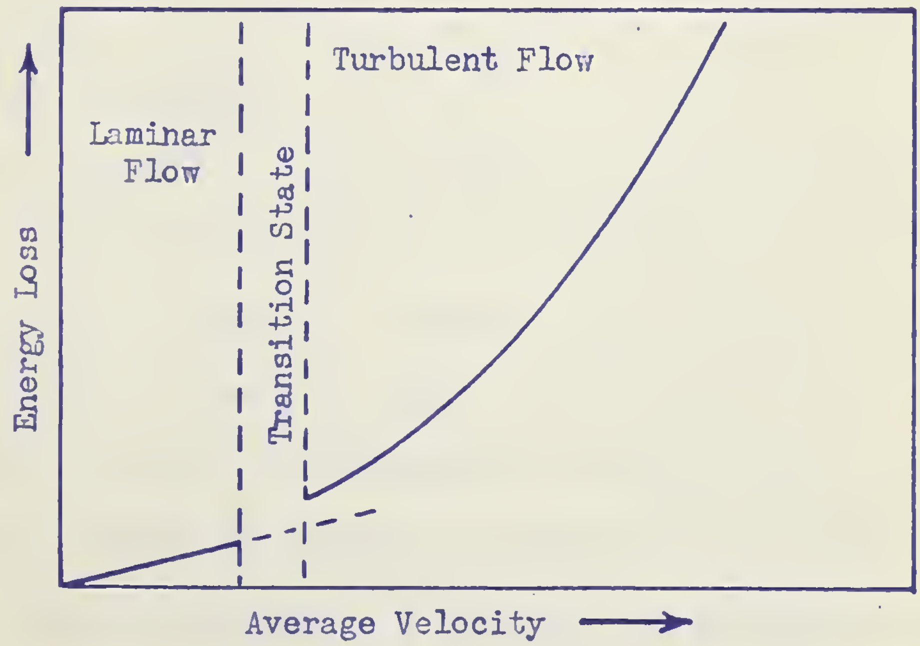


PLATE 2

TYPES OF FLOW

Based on permeability tests, Burmister(18) concluded that in nature flow through silt takes place in the laminar state. As the material used in the present testing program was a fine silt, and because (as mentioned previously) the optimum grain size for producing ice lenses falls in this range, only laminar flow will be considered.

Viscosity is defined as " . . . that property of a fluid by virtue of which it offers resistance to shear stress" (17). Viscous effects must, then, contribute to the energy losses which occur in a flowing liquid. The shearing stress due to viscosity is governed by Newton's law of viscosity.

$$\tau = \mu v/y \quad \text{(II.3)}$$

where τ is the shearing stress, μ is the viscosity, and v is the change in velocity over a distance y normal to the direction of flow. Dividing through by the unit weight of the liquid, equation (II.3) becomes

$$\tau/\gamma_L = \mu v/y\gamma_L \quad \text{(II.4)}$$

This is an expression for the energy loss per unit weight of the liquid. For μ, y, and γ_L constant, the energy loss is proportional to the change in velocity. Providing the geometry of the velocity distribution curve remains similar, the average velocity change will be a constant function of the maximum velocity change v. Therefore, the energy loss per unit weight of liquid is proportional to the average change in velocity. If y is zero at some fixed boundary where the velocity of flow is zero, then the energy loss is proportional to the average velocity: the condition given previously,

as that defining laminar flow. Thus, in laminar flow, the energy loss as given by equation (II.2) is due to the viscosity of the fluid.

Another characteristic of laminar flow is that flow lines (the paths taken by individual particles in passing through a given system) do not cross. It follows that the continuity equation applies to flow through a flow tube (the space bounded by flow lines). Consequently, the mass per unit time passing through any section of a flow tube is constant for steady flow conditions. Thus, knowing the rate of flow and the geometry of the flow tube, the average velocity at any section can be determined.

Summing up, it can be said, that for the steady laminar flow of an incompressible liquid in a flow tube, equation (II.2) may be used to determine the energy loss due to the viscosity of the fluid.

When a flow tube is straight and of uniform size, flow will be one-dimensional. Furthermore, for the conditions stated above, the average velocity will be the same at every section along the flow tube. The velocity term in equation (II.2) will be zero, so that for one-dimensional flow that equation becomes

$$H = (z_1 - z_2) + (h_1 - h_2) \qquad \text{(II.5)}$$

In flow equations, energy loss may be included in a term called the hydraulic gradient. This is equal the energy loss per unit distance in the direction of flow. Thus

$$i = H/L \qquad \text{(II.6)}$$

where i is the hydraulic gradient and H is the energy loss over a

distance L. As L is independent of factors affecting energy loss, all the assumptions governing the energy loss will be inherent in the hydraulic gradient.

Liquid Flow in Pipes

It can be shown(17), that for steady laminar flow through uniform circular horizontal pipes, the average velocity V, is given by

$$V = \frac{R^2}{8\mu}\left(\frac{\Delta p}{L}\right) \quad \ldots\ldots\ldots\ldots \quad \text{(II.7)}$$

where R is the radius of the tube, μ is the viscosity of the liquid, and Δp is the pressure drop over a distance L. The derivation assumes that the velocity of liquid in contact with a boundary surface is zero. By substituting $p = h\gamma_L$ from equation (II.1), we get

$$V = \frac{R^2\gamma_L}{8\mu}\ \frac{\Delta h}{L} \quad \ldots\ldots\ldots\ldots \quad \text{(II.8)}$$

By substituting from Equations (II.5) and (II.6), we can write

$$V = (R^2\gamma_L/8\mu)i \quad \ldots\ldots\ldots\ldots \quad \text{(II.9)}$$

The terms inside the brackets are physical properties of either the pipe or the liquid. This equation is applicable to vertical or inclined pipes as well as horizontal ones.

Darcy's Law

In the field of soil mechanics, flow equations are based on Darcy's law (19, 20), which in turn, was based on the observation of water moving vertically downward through horizontal sand filter beds. The flow equation may be written as follows.

$$Q = k\ i\ A\ t \quad \ldots\ldots\ldots\ldots \quad \text{(II.10)}$$

Where Q is the volume of flow occurring in time t through a total cross-section area A, under the hydraulic gradient i. The term k is the constant of proportionality in the equation. Letting the rate of flow $q = Q/t$, it follows that $q = k\ i\ A$ and $q/A = k\ i$, where q/A has the units of velocity. Designating this term the superficial velocity v, the equation becomes

$$v = k\ i \quad \ldots\ldots\ldots\ldots \quad (II.11)$$

where k is the Darcy coefficient of permeability and i is the hydraulic gradient. In an apparatus such as that shown in Plate 3, the superficial velocity will be equal to the velocity of the liquid as it approaches and after it emerges from the soil sample. Within the specimen part of the total cross-section area is occupied by soil particles, so that the average velocity within the pores will be greater than the superficial velocity.

Letting V_v be the volume of voids and V the total volume of the soil mass, the porosity n is defined by (19)

$$n = V_v/V \quad \ldots\ldots\ldots\ldots \quad (II.12)$$

Assuming that the distribution of solid area A_s, and void area A_v on a plane through the sample, is the same as the distribution of solid volume V_s and void volume V_v throughout the specimen, it follows that $n = V_v/V = A_v/A$. Hence $A_v = n\ A$. Applying the concept of continuity to the system gives $q = v\ A = v_s\ A_v$. This may be rewritten as $v = v_s\ (A_v/A)$. Substituting $n = A_v/A$ gives

$$v = n\ v_s \quad \ldots\ldots\ldots\ldots \quad (II.13)$$

where v_s is the seepage velocity. This term has practical

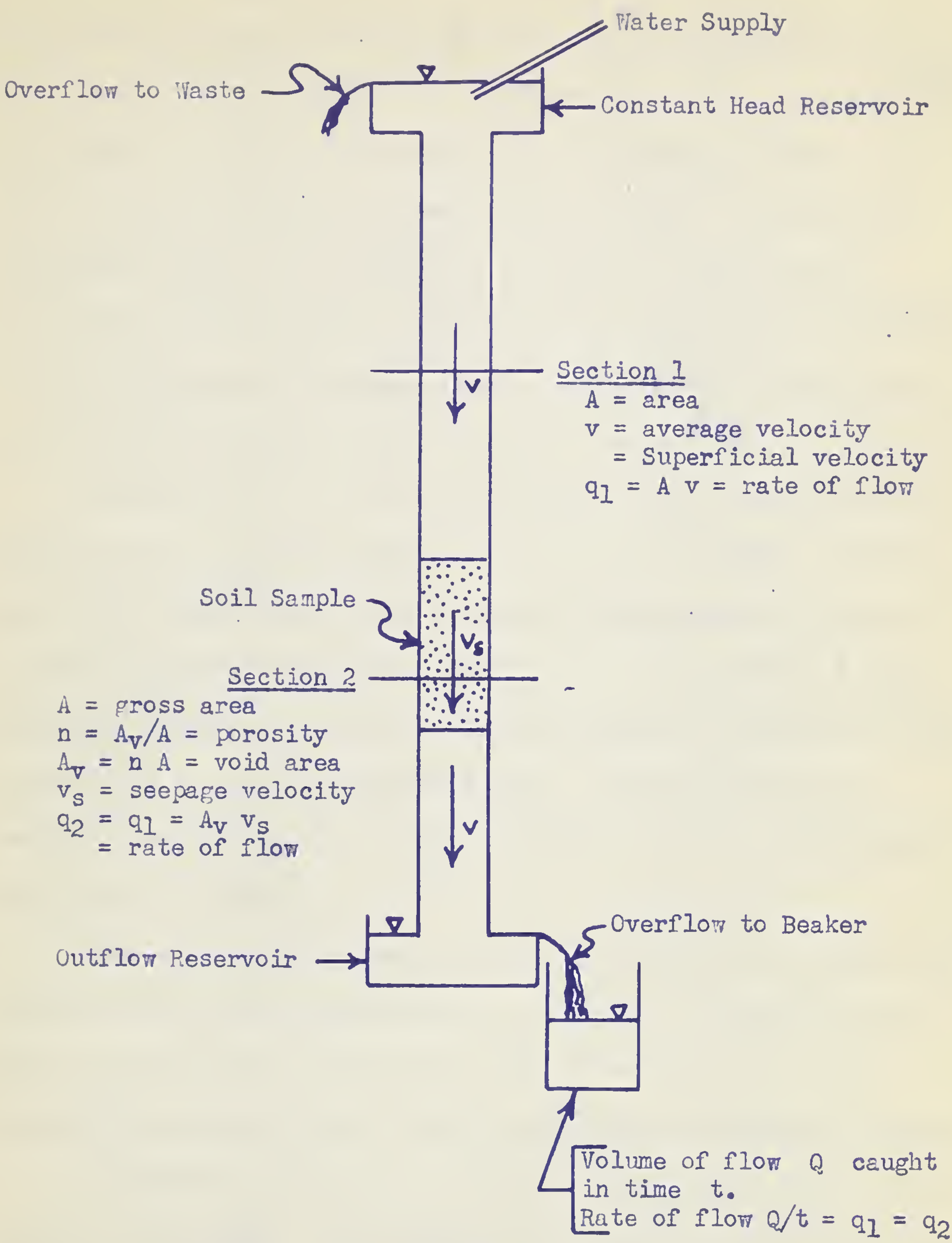


PLATE 3

LIQUID VELOCITIES
IN A TYPE OF PERMEABILITY APPARATUS

significance in that it represents the rate at which an element of liquid moves in the direction of the flow path. It may be considered an average velocity based on the sum of displacement vectors which trace the path of a particle through the specimen. Displacement components normal to the direction of flow are considered to balance out statistically. The significance of superficial velocity is that it represents the quantity of liquid passing through a unit of cross-section area of sample, in unit time.

Equation (II.11) gives Darcy's law in its simplest and most general form. As stated, the terms i, and v, correspond to cause and effect, respectively. The physical characteristics of the soil and the permeating liquid are implicit in k. The units of k are dependent on the units used to express energy loss, and consequently on the units of hydraulic gradient (21). As developed in this chapter, the hydraulic gradient is unitless. This gives permeability the units of velocity.

The similarity between equation (II.9) for flow in pipes and equation (II.11) for flow in soils, is apparent. Considering the former to be a special case of the latter, it follows that the assumptions governing pipe flow will apply to soil moisture movements.

In equations (II.9) and (II.11), the hydraulic gradient is common. On the basis that superficial velocity is proportional to the seepage velocity, it can be accepted that the average velocity in the pipe flow equation is similar to the superficial velocity in the Darcy's law equation. Finally, the permeability k corresponds to the term $\frac{R^2\gamma_L}{8\mu}$. If k is multiplied by μ/γ_L, the resulting

quantity K will be independent of the permeating liquid. When the liquid is water, the unit weight may be considered to be independent of pressure and temperature. In the metric system it is equal to one, therefore, it may be ignored numerically. Permeability may be corrected to the viscosity at some standard temperature μ_s, without altering the permeability units, by using the following equation (19)

$$k(\text{corrected}) = k \frac{\mu}{\mu_s} \quad \ldots \ldots \ldots \quad (\text{II.14})$$

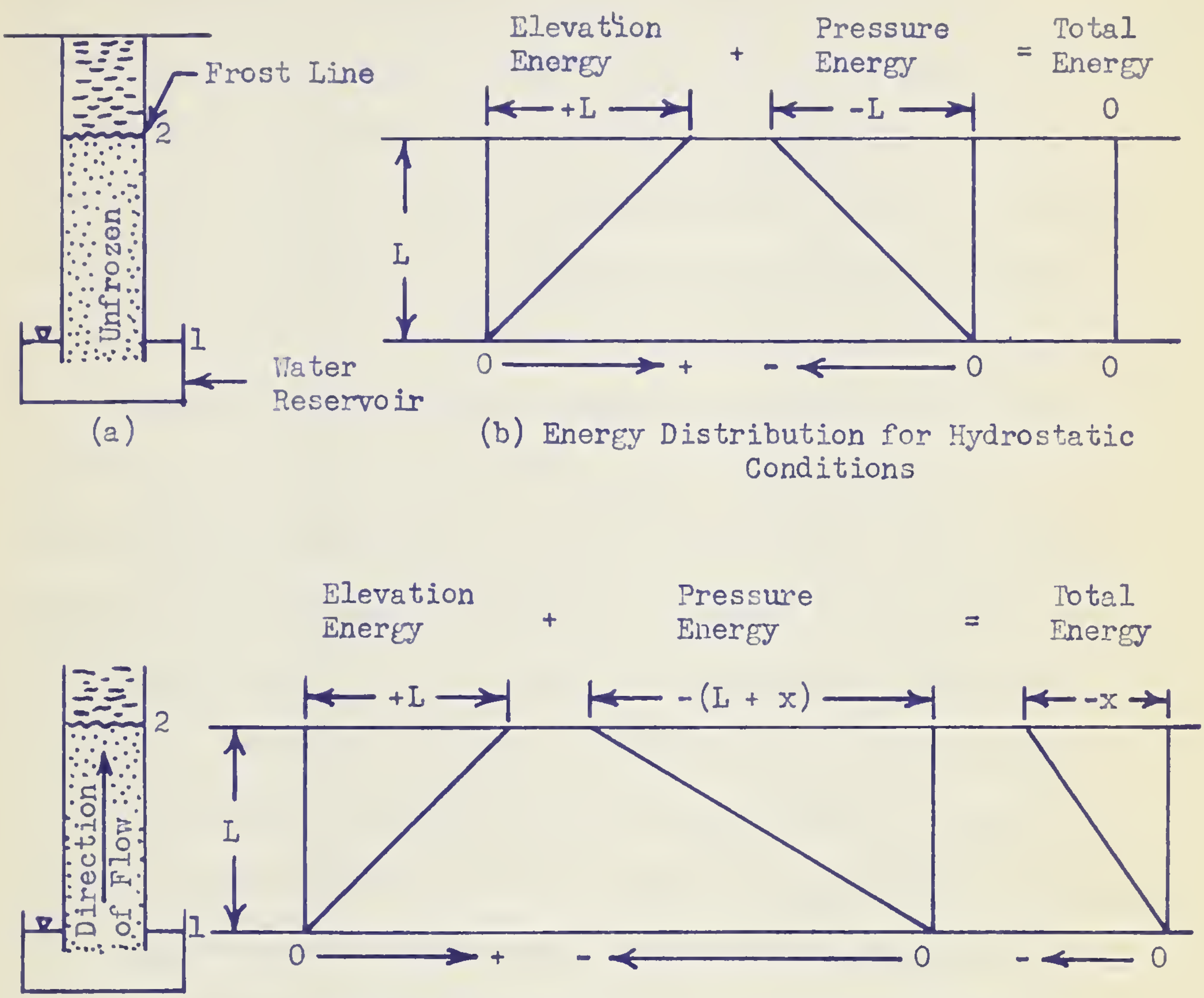
It being difficult to define or determine physical constants which are representative of a soil sample, permeability is generally determined directly by field or laboratory tests. It has been determined by Taylor (19), that the following approximate relationship between permeability and void ratio, e (volume of voids divided by volume of soil solids) applies to sands.

$$k_1 : k_2 = \frac{{e_1}^3}{1 + e_1} : \frac{{e_2}^3}{1 + e_2} \quad \ldots \ldots \quad (\text{II.15})$$

It has been shown by Lambe (22), that for kaolinite, this relationship is not linear. He explains this on the basis of adsorption, a surface phenomenon associated with particles of colloidal size. The relationship is sufficiently close to being linear so that equation (II.15) may be used as an approximation. At any rate, Darcy's law will apply if the soil structure remains constant and if the soil is homogeneous and saturated (i.e. the soil voids are filled with water).

Water Flow in Soils

With ice segregation moisture generally moves against gravity, from the water table to the frost line, as illustrated in Plate 4(a).



(a)

(b) Energy Distribution for Hydrostatic Conditions

(c) Energy Distribution for Darcy Type Flow Upwards

PLATE 4

ENERGY PROFILES FOR VERTICAL SPECIMENS

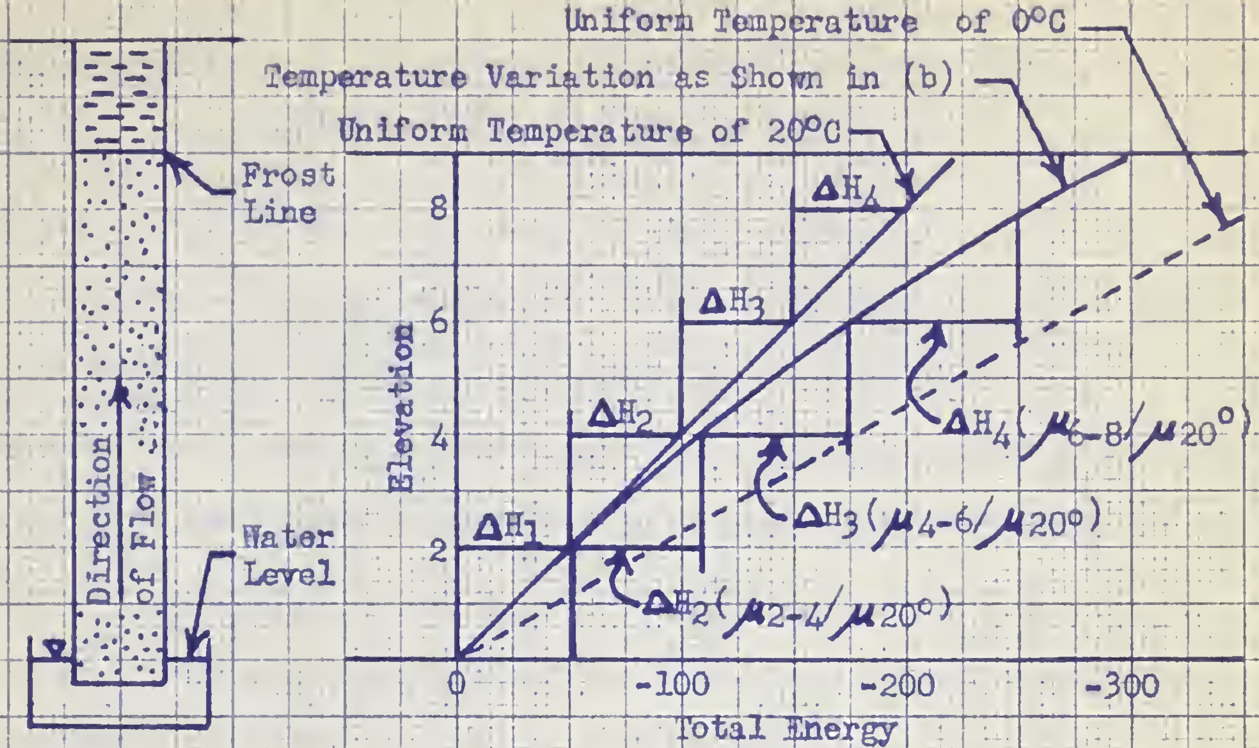
Point 1 represents a free water surface at atmospheric pressure. The frost line at any given time is represented by point 2. Under hydrostatic conditions the total energy will not vary between 1 and 2, and will be equal to zero when the water level in the reservoir is taken as the datum for elevation energies. Elevation energy will increase linearly from zero at the reservoir to a value L at the frost line, where L is the vertical distance between them. It follows that the pressure energy must be equal and opposite to the elevation energy. At an elevation of x cm. above the free water surface, there can be upward movement of water only when the negative pressure in the water at that point exceeds -x cm. of water. Furthermore, subject to the conditions inherent in Darcy's law, the change in total energy with respect to elevation above the free water surface should be independent of that elevation. The total energy profile should be linear, starting at zero at the free water surface and increasing negatively in the direction of the frost line. These relationships are shown in Plate 4(a) and (b).

In the case of ice segregation, the temperature will vary along the flow path, from the water temperature at the water table to freezing temperature at the frost line. The viscosity, being dependent on temperature, will consequently vary along the flow path. It can be shown, using equations (II.11) and (II.14), that, other factors being constant, the hydraulic gradient is directly proportional to the viscosity. Furthermore, from previous consideration of the hydraulic gradient, it follows that the total

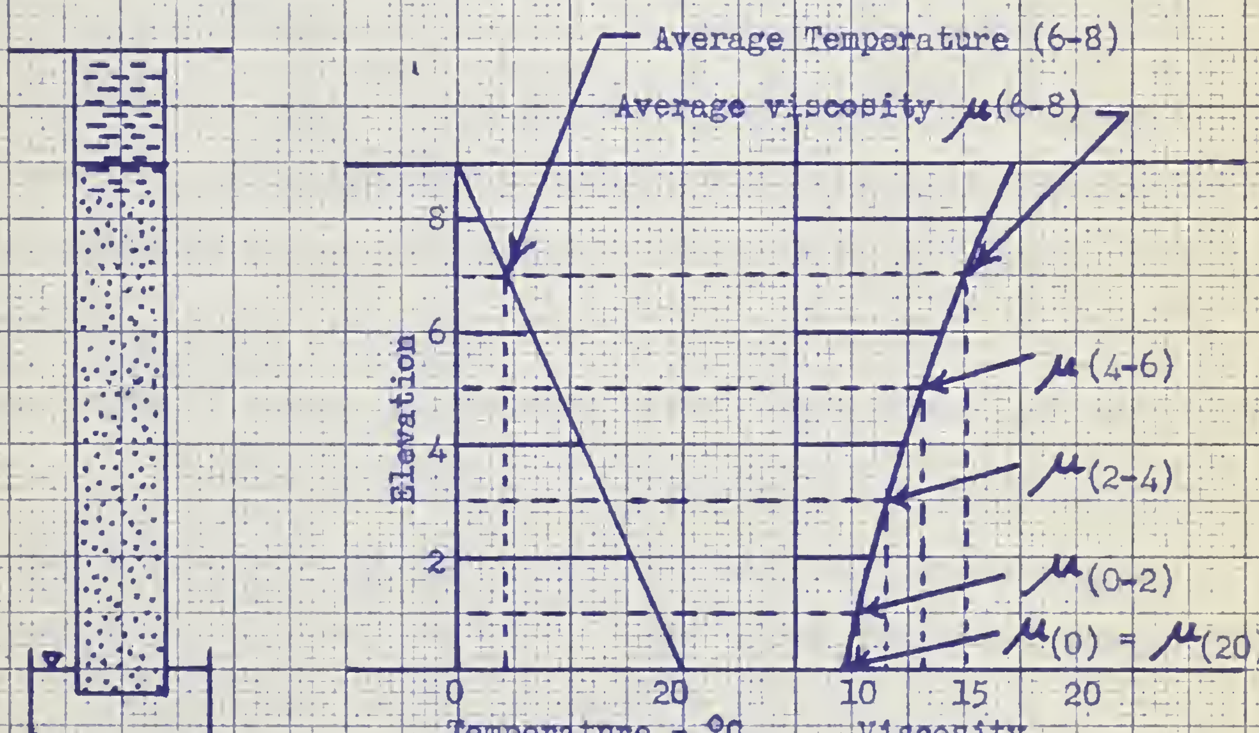
energy loss is proportional to the viscosity. If the total energy loss between two points is H_1 when the average viscosity between those points in μ_1, then the total energy loss H_2, corresponding to any other average viscosity μ_2, will be given by the following equation.

$$H_2 = H_1 \frac{\mu_2}{\mu_1} \quad \ldots\ldots\ldots\ldots\ldots \quad \text{(II.16)}$$

This equation may be used to determine the effect of temperature variation on the total energy profile. This has been done in Plate 5. The striaght line profile shown in Plate 5(a) is the type of profile to be expected for Darcy type flow under uniform temperature conditions. A linear variation of temperature with depth has been assumed, and will exist for steady state heat flow through a homogeneous sample. By taking temperatures from the temperature profile and the corresponding viscosities from the International Critical Tables, the viscosity profile was constructed. The profiles were then divided into increments such that the viscosity at the mid-point of the increment could be assumed to be the average across the increment. Using this viscosity, equation (II.16) was solved for the corresponding total energy loss. The total energy profile corresponding to the linear temperature variation was obtained by taking the total energy at the reservoir surface and adding successively, the incremental total energy losses (See Plate 5). As elevation energy is independent of viscosity, changes that occur in the total energy loss due to variations in viscosity must also occur in the pressure energy loss, giving a non-linear pressure energy profile. If a total energy profile is obtained experimentally for a temperature



(a) Total Energy Profiles



(b) Temperature and Viscosity Profiles

PLATE 5

EFFECT OF TEMPERATURE ON TOTAL ENERGY DISTRIBUTION

which varies along the flow path, it may be corrected to a uniform temperature condition by applying equation (II.16). When this profile is linear, Darcy's law is valid.

Pressure energy can be converted to pressure by multiplying by the unit weight of water. In the metric system, the two quantities will have the same magnitude. In soil mechanics, the pressure in soil water is referred to as "pore water pressure" or "neutral pressure". Pressure transmitted from particle to particle is called "effective pressure". The sum of the two is termed "total pressure". The variation of these quantities along the flow path in a homogeneous sample has been outlined by Rutledge(22) for various static and steady flow conditions. Using his approach, neutral, effective and total pressure profiles were constructed for the case of water moving upward through a homogeneous sample in accordance with Darcy's law(See Plate 6). It should be noted that the effective pressure is not constant throughout the length of the sample. Because effective pressure is related to soil density and void ratio by way of consolidation[1], there will generally by a tendency for non-homogeneity to develop. Whether effective stresses produce significant changes in the soil structure or not depends on the magnitude of the stress variation, on the consolidation characteristics of the material, and

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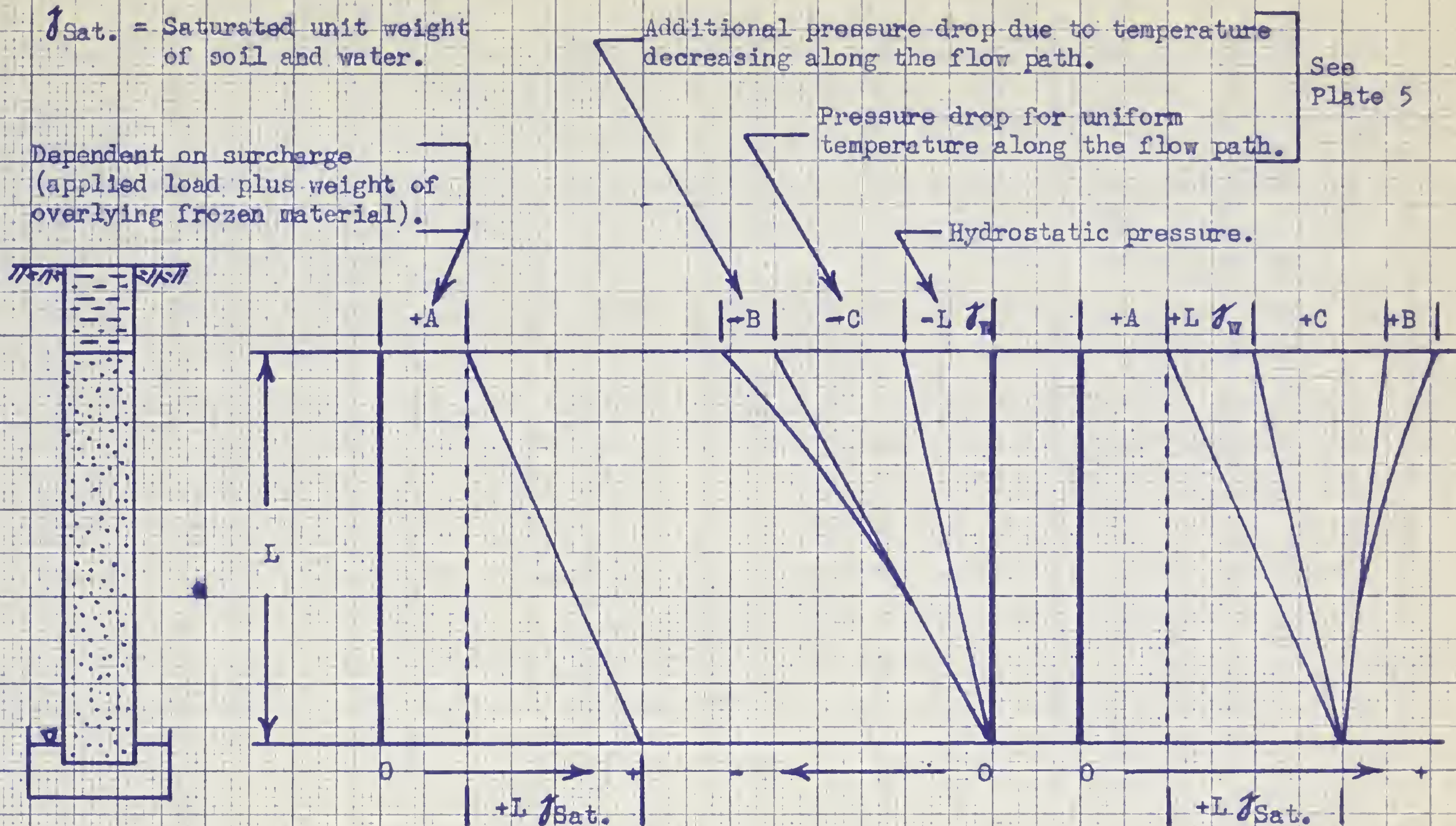
[1] A theoretical treatment of consolidation is given by most standard textbooks on Soil Mechanics.

on the previous stress history of the material. These factors have to be evaluated for the particular situation being considered.

Another complication is inherent in the existence of negative stresses in the soil voids. Capillary forces will be present where the specimen is exposed to air. For a soil specimen confined by a stack of rings, the perimeter of the specimen will be exposed to air. It is here that capillary or surface forces will be present in menisci in the soil voids. Negative pressures beyond those for which the menisci are fully developed, will result in the menisci receding into the specimen, thereby desaturating it.

With capillary tubes it has been shown that the height of capillary rise is inversely proportional to the diameter of the tube. Therefore, the maximum negative stress that can exist in the liquid at equilibrium is inversely proportional to the tube diameter. In a soil sample, the largest pores would be the first to unsaturate, followed by others in order of decreasing diameter. Now consider a homogeneous sample in which the neutral pressure varies as shown in Plate 6. If at some elevation the stresses are sufficient to unsaturate the sample, then the degree of saturation (volume of water over volume of voids) will decrease with distance above that elevation due to the increasing negative pressures. Below that elevation, the sample will remain saturated and Darcy's law will apply. For unsaturated flow the boundaries of the flow channels are no longer defined by the geometry of the soil voids. Part of the void space is occupied by air and cannot be considered available for water flow. Hence, for a given



Total pressure (P) = Neutral Pressure (P_n) + Effective Pressure (P_e)

PLATE 6

NEUTRAL, EFFECTIVE AND TOTAL PRESSURES
FOR THE CASE OF UPWARD FLOW UNDER NEGATIVE PRESSURES

rate of flow, the seepage velocity will increase with a decreasing degree of saturation. As the process of desaturation is selective as to the size of pores drained, there will be no simple relationship between superficial velocity and seepage velocity. For example, if a sample has a degree of saturation of fifty percent for a given rate of flow, it might be expected that the seepage velocity would be doubled as compared to the same rate of flow in the saturated condition. However, other factors being constant, average velocity increases as the size of the flow channel squared (See equation (II.7). Therefore, for a given rate of flow, the quantity of flow passing through channels which are saturated when the overall degree of saturation is fifty percent, will be more than double the flow through the same channels when the degree of saturation is one hundred percent. The actual seepage velocity for unsaturated conditions will be greater than the seepage velocity determined by applying porosity and degree of saturation corrections to the superficial velocity. The problem of determining some characteristic flow channel dimensions for evaluating this difference is analogous to the problem of selecting measurable physical quantities to define the permeability of a soil. At any rate, the presence of air in the soil acts as an obstruction to the water, and therefore decreases the permeability of the soil. For this condition, the permeability is a function of the negative stress in the pore water. It is also a function of the moisture content because this quantity is related to the air content, to the degree of saturation, and consequently, to the negative stress. Darcy's law for the case of

unsaturated flow may be written as follows(15):

$$v = k_u i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (II.17)$$

The unsaturated coefficient of permeability is designated by k_u, and the terms v and i have the same meaning as in equation (II.11). The superficial velocity, v (equal to q/A) is therefore the volume of water passing through unit area in unit time. It follows that for steady state flow, the superficial velocity will be constant for either saturated or unsaturated flow. For either condition, if the seepage velocity and the hydraulic gradient are known or can be determined, the former divided by the latter will yield a permeability value. If this is repeated for different hydraulic gradients, then, by means indicated earlier in this chapter, it can be determined if saturated or unsaturated conditions prevail. For a number of factors associated with soil water movement, Plate 7 indicates the type of variation that would be expected for steady laminar flow, in both the saturated and unsaturated condition.

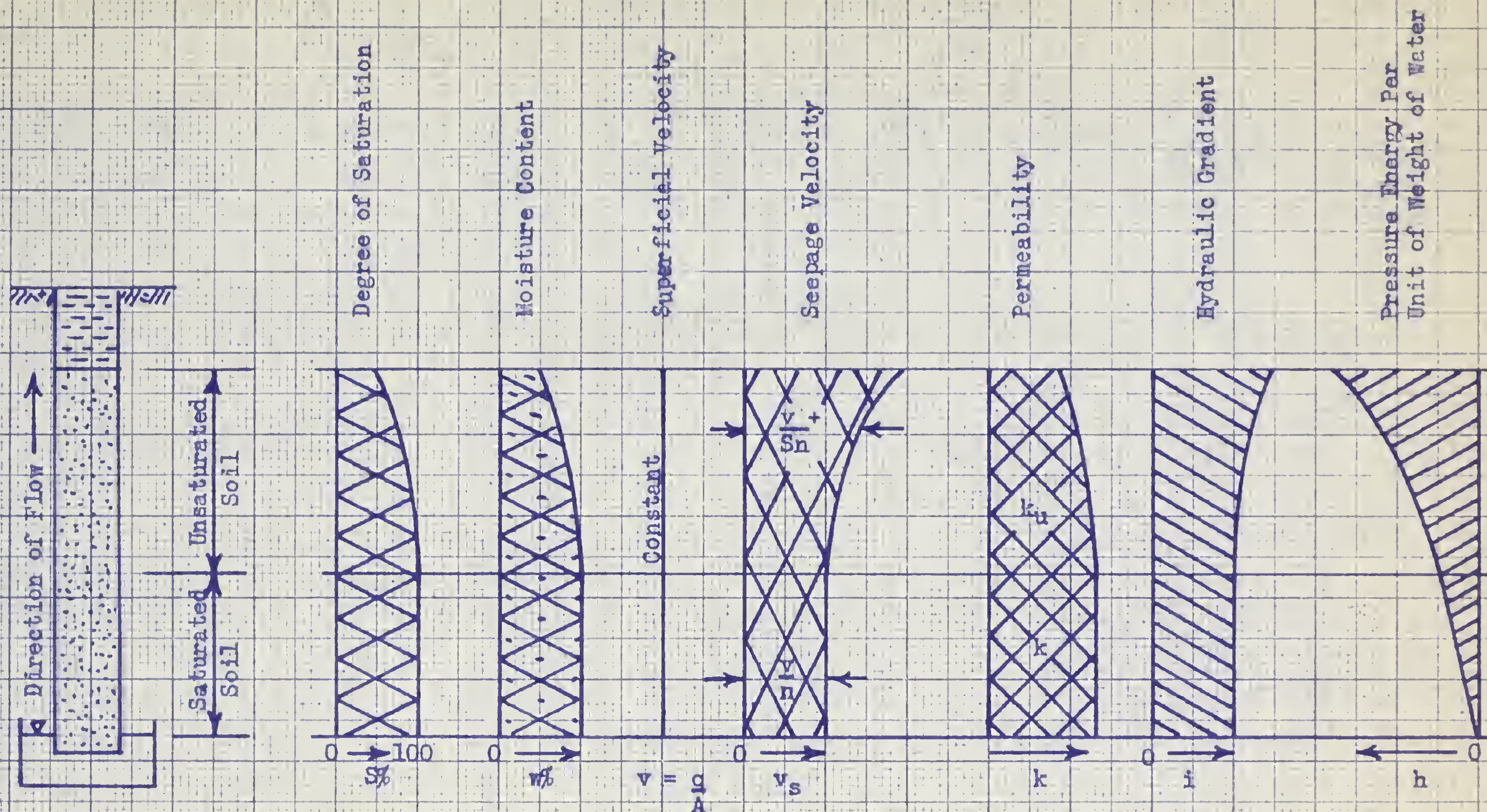


PLATE 7

A QUALITATIVE COMPARISON BETWEEN SATURATED AND UNSATURATED FLOW FOR ONE-DIMENSIONAL, LAMINAR, STEADY STATE FLOW AT CONSTANT TEMPERATURE

CHAPTER III

APPARATUS AND INSTRUMENTATION

The frost cabinet for testing specimens was built into a cold room. The top of the specimen was exposed to the cold room temperature while the bottom was open to normal room temperature of the adjoining room which housed the temperature and pressure measuring apparatus. (See Plate 8).

The Cold Room

The cold room had one "walk-in" type of door and a smaller one opening into the adjoining room. Cooling was provided by a Freon refrigeration unit. The air in the cold room was circulated through the cooling coils by means of fans. Temperatures were controlled by means of a thermostat having a range of plus 12 to minus 35 degrees Fahrenheit. The computations for both mean and median temperatures in the cold room are given in Appendix B, along with a plot showing the variation of temperature with time. The following table summarizes the results.

TABLE I

TEMPERATURE CHARACTERISTICS OF THE COLD ROOM

Median Temp. °F	Max. Temp. °F	Min. Temp. °F	Temp. Range °F	Frequency of Temp. Cycle Minutes
-7.6	-4.0	-9.1	5.1	7.8*
+4.3	+8.1	+2.5	5.6	6.5
+13.8	+17.9	+11.0	6.9	7.1

*The frequency was averaged over at least three cycles.

Note: Temperature was measured at a point just above the frost cabinet.

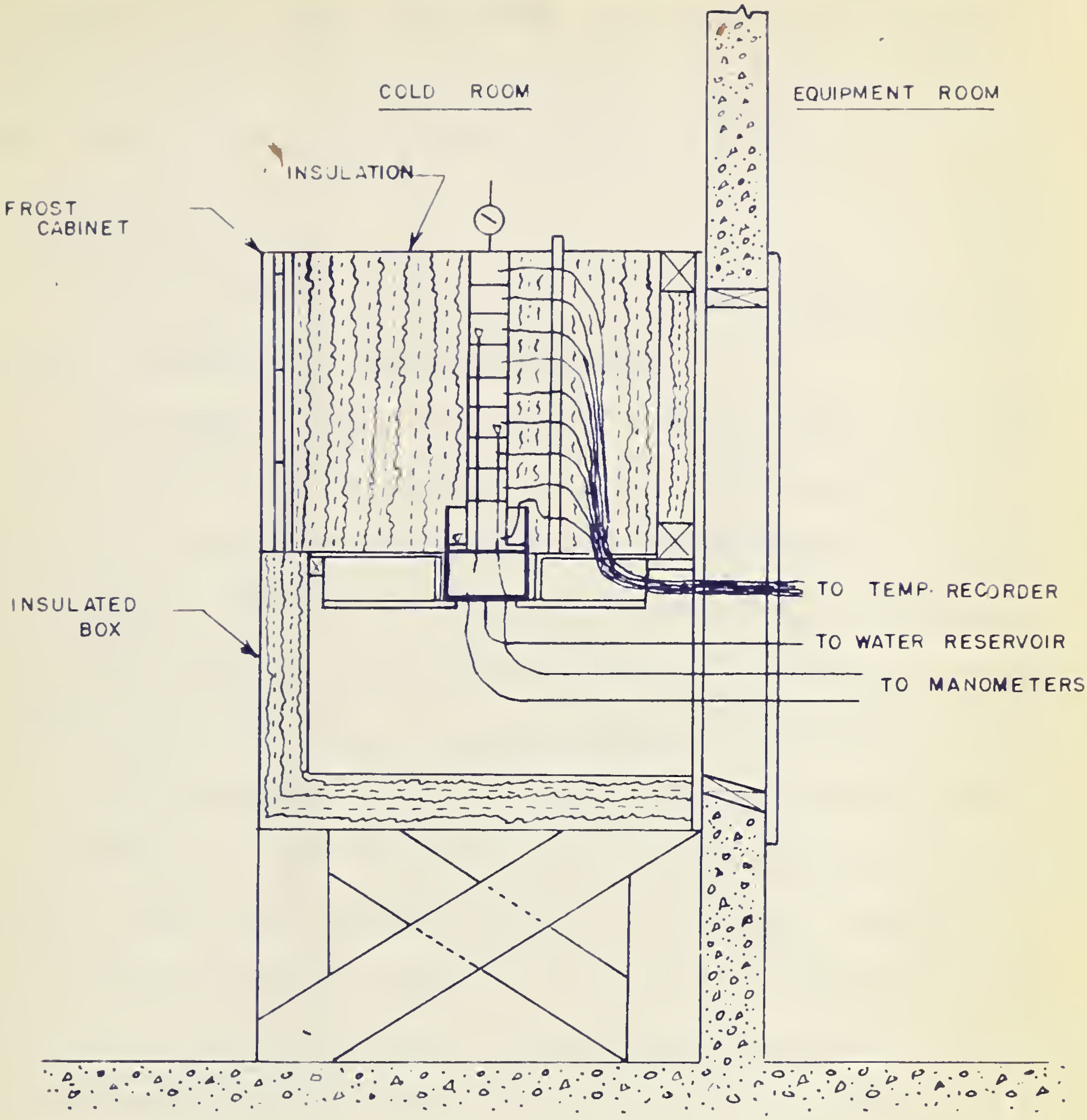


PLATE 8

SCHEMATIC DIAGRAM of FROST CABINET

In previous experience, no temperature fluctuations were registered by thermocouples located one quarter inch below the sample surface. Below this point, the cold room temperature fluctuations of the type shown in Table I, will have no effect.

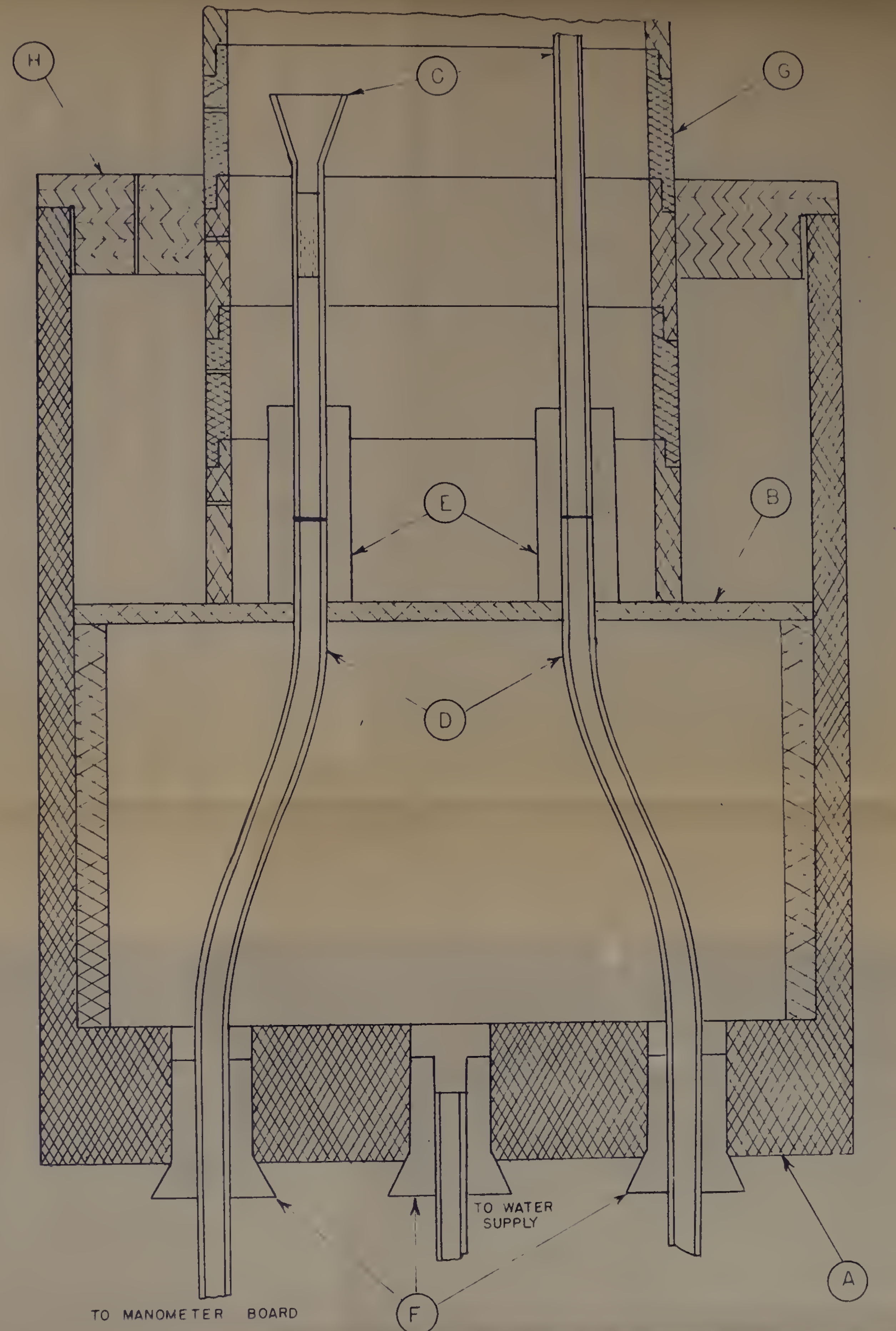
The Frost Cell

This apparatus is shown in Plate 9. Detail drawings of the various components are included in Appendix A.

The sample container consisted of a stack of three inch diameter lucite rings which fitted together as shown. This over-lap was designed to prevent lateral shifting of the rings during the placing of the sample. A loose fit was provided between rings so that they could easily separate when heaving occurred in the sample. The small drilled hole in each ring was for the insertion of a thermocouple.

The test specimen was supported by the porous bronze plate in the water reservoir. The water level was maintained above this plate so that water was made available to the sample. Manometer lines passed through the bottom of the reservoir, through the bronze plate and to the tapping points. The reservoir cap served to keep insulation out of the reservoir and also to check the diffusion of moisture into the surrounding insulation.

The water reservoir was connected to a water supply bottle and a stand pipe, both in the equipment room. The required water elevation was marked on the stand pipe. This was maintained by adding water to the supply bottle. With this system the water supply could be controlled without entering the cold room or disturbing the test specimen.



PIECE	NAME	QUAN.
A	RESERVOIR	1
B	SAMPLE SUPPORT	1
C	TAPPING POINT	5
D	MANOMETER PART	5
E	COUPLING	5
F	RUBBER STOPPER	6
G	SAMPLE CONTAINER	1
H	RESERVOIR CAP	

PLATE 9
ASSEMBLY of APPARATUS in
FROST CABINET

The frost cell (without a sample) is shown sitting in its cradle, on Plate 10.

Manometers

The type of manometer used, was a modification of a simple water over mercury U-tube. One branch consisted of a one half inch inside diameter mercury reservoir, while the other branch was one millimeter inside diameter capillary tube with connections on top for de-airing the apparatus and connecting the polythene lines from the tapping points in the specimen. The rubber tubing that connects the two branches was necessary for the de-airing procedure which will be discussed in the next chapter. The use of mercury in the manometers in conjunction with the capillary sections was designed to give a minimum of time lag between changes in pressure in the sample and the response to those changes by the manometers. The length of the capillary section was such that the water-mercury interface was contained within that section for all conditions met during the testing. Plate 11 shows the final form of the manometers used.

Polythene lines were taken off above the capillary section and connected to the glass tubing which passed through the water reservoir to the tapping points. Rubber couplings above the porous bronze plate made the connection between the manometer leads and the tapping points. The use of couplings allowed some adjustment to the height of individual tapping points, facilitated the changing of points and formed a non-rigid connection so that the tapping points could be lifted if subjected to frost heaving. Furthermore the de-airing of

PLATE 10

INSTRUMENTATION IN FROST CABINET

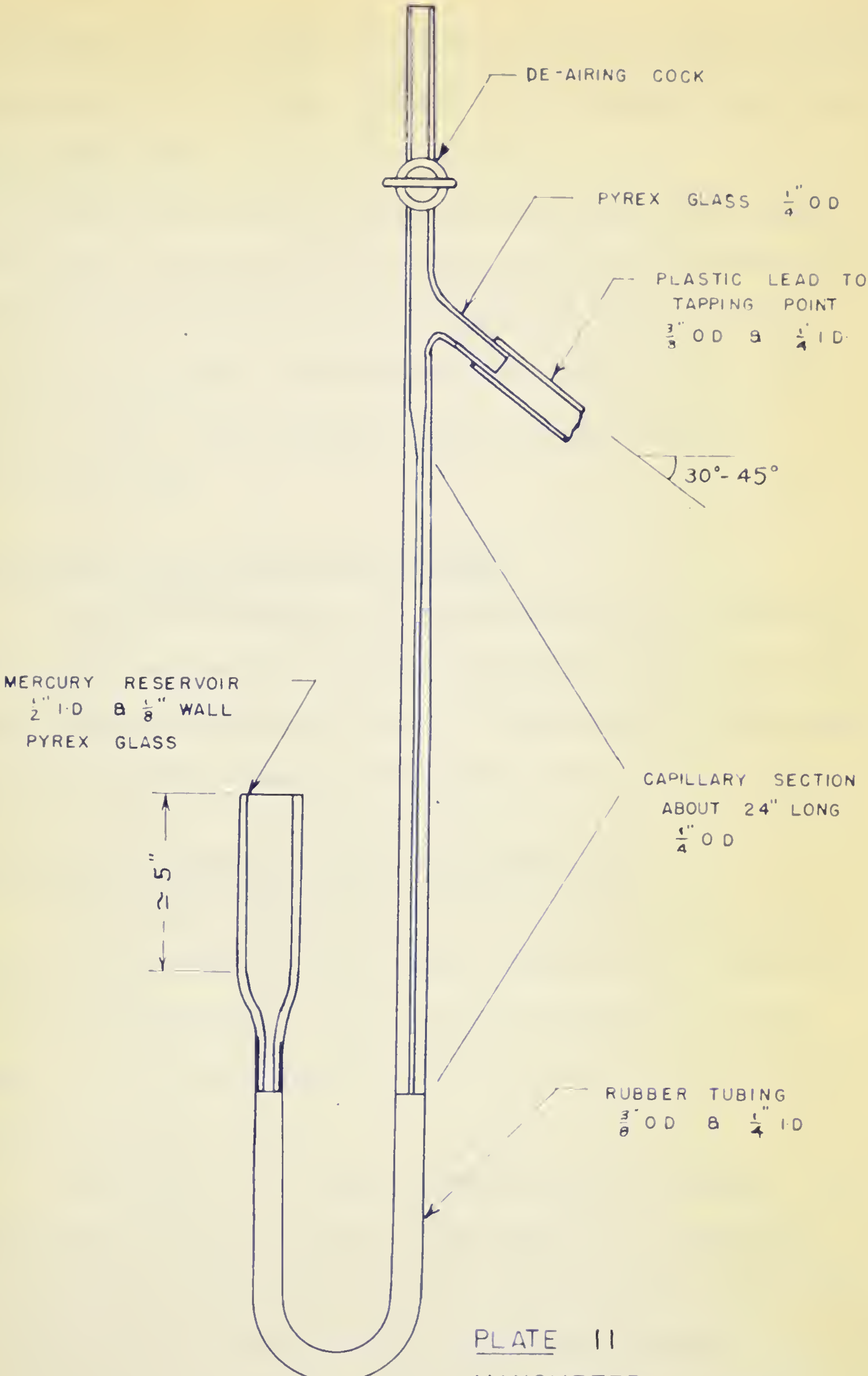


PLATE II

MANOMETER DETAIL

the manometers was facilitated by doing the tapping points separately from the rest of the system. See Plate 9 for manometer connections at the frost cell.

The tapping points were made from one quarter inch diameter glass tubing. One end was belled out to one half inch diameter and a tight roll of fine wire mesh was fitted into the throat below the bottom of the bell. The stem was then cut off to leave the required length. These tapping points were satisfactory in preliminary tests.

Measurement of Heave with an Extensometer

An Ames dial mounted on a ring stand was used to measure the heave in the test sample. The shaft of the dial rested on a metal plate which was placed across the top of the sample for that purpose. It was necessary to enter the cold room to read the dial.

Temperature Measurements by Means of Thermocouples

Temperatures were measured with a "Brown Electronik Strip Chart Recorder" (Serial 534449, Model 153X64P16-X-41), using iron-constantan thermocouples. The "fused bead" thermocouples were made of No. 24 B and S gage wire. The same wire was used for the leads going to the recorder.

The recorder could handle up to sixteen thermocouples. The temperature at each thermocouple was recorded every four minutes. The charts had a time scale as well as the temperature scale with a range of minus 50 degrees to plus 100 degrees Fahrenheit.

The calibration of the thermocouples and recorder was done

by stirring a fifty percent mixture of ice and water with the thermocouples while the temperature was being recorded on the chart. The results of two such calibrations is given in Appendix B. Assuming that the water was at 32°F., the recorded temperatures averaged 0.5 and 1.3 degrees too high, respectively. Deviation from the average was small.

The Frost Cabinet

The frost cabinet supported the frost cell so that the water reservoir protruded down into an insulated box which was open to the equipment room and normal room temperature. The top part of the frost cabinet was a shell for confining loose vermiculite insulation which was placed to the height of the test specimen, leaving the top of the specimen exposed to the cold room temperature. The leads to the temperature and pressure measuring apparatus were taken from the sample into the bottom of the frost cabinet and out into the equipment room.

CHAPTER IV

PROCEDURES

Installation and Checking of Manometers

The glassware was cleaned by washing with a saturated solution of sodium bichromate and then flushing with distilled water. When the manometers were mounted on the panel, precautions were taken to insure that they were plumb. After assembling the mercury reservoir, rubber section and capillary tube, mercury was poured in and the trapped air was worked out. The level of the mercury in the capillary section was lower than that in the reservoir due to capillary effects. As piezometric pressures were to be determined using differences in readings, capillary effects would cancel out provided that they were constant. To check this, the reservoir was raised by increments throughout the heighth of the capillary section. For each increment the difference in elevation between the mercury in the reservoir and that in the capillary section was determined. The procedure was repeated at several decreasing reservoir heights. There was little deviation between values obtained for the elevation difference in the various capillary sections with the mercury level rising, and with one exception, the same was true when the mercury level was falling. This was taken to indicate uniformity of the diameter throughout the length of the capillaries. The average elevation difference with the mercury level rising was 0.8 centimeters; with the mercury level dropping, 0.6 centimeters, barring the one exception. The results of these tests are given in Appendix B.

Centimeter tapes were used for determining elevatinns on the manometers. These were fixed to the panel with their zero marks at the same elevation. (See Plate 12.)

The manometers and the water supply system were then set up as shown in Plate 13, with the exception that the tapping points, rubber couplings and the porous bronze plate were removed. The apparatus was then ready to be charged with water and de-aired.

De-airing the Water Supply System

After the water reservoir was placed in the frost cabinet, the water supply bottle and the stand pipe were connected as shown in Plate 13. The porous bronze plate was removed and de-aired distilled water was poured into the reservoir until it was several inches deep. By blocking off the stand pipe and applying a vacuum to the water supply bottle a flow of water was obtained which removed the air between the reservoir and the bottle. To de-air the remainder the supply bottle was stoppered and the vacuum was applied at the stand pipe. The water reservoir was filled to a level above the position of the porous bronze plate. This plate was de-aired by boiling it in water under a vacuum. It was then slid out of the de-airing dish into the water reservoir, where it was seated.

The procedure differed for Test 9, where no effort was made to de-air the porous bronze plate. It was left in place while the rest of the de-airing procedure outlined above was carried out.

As long as the water level reamined at or above the bronze plate, it was not necessary to repeat the de-airing of the water supply system between tests.

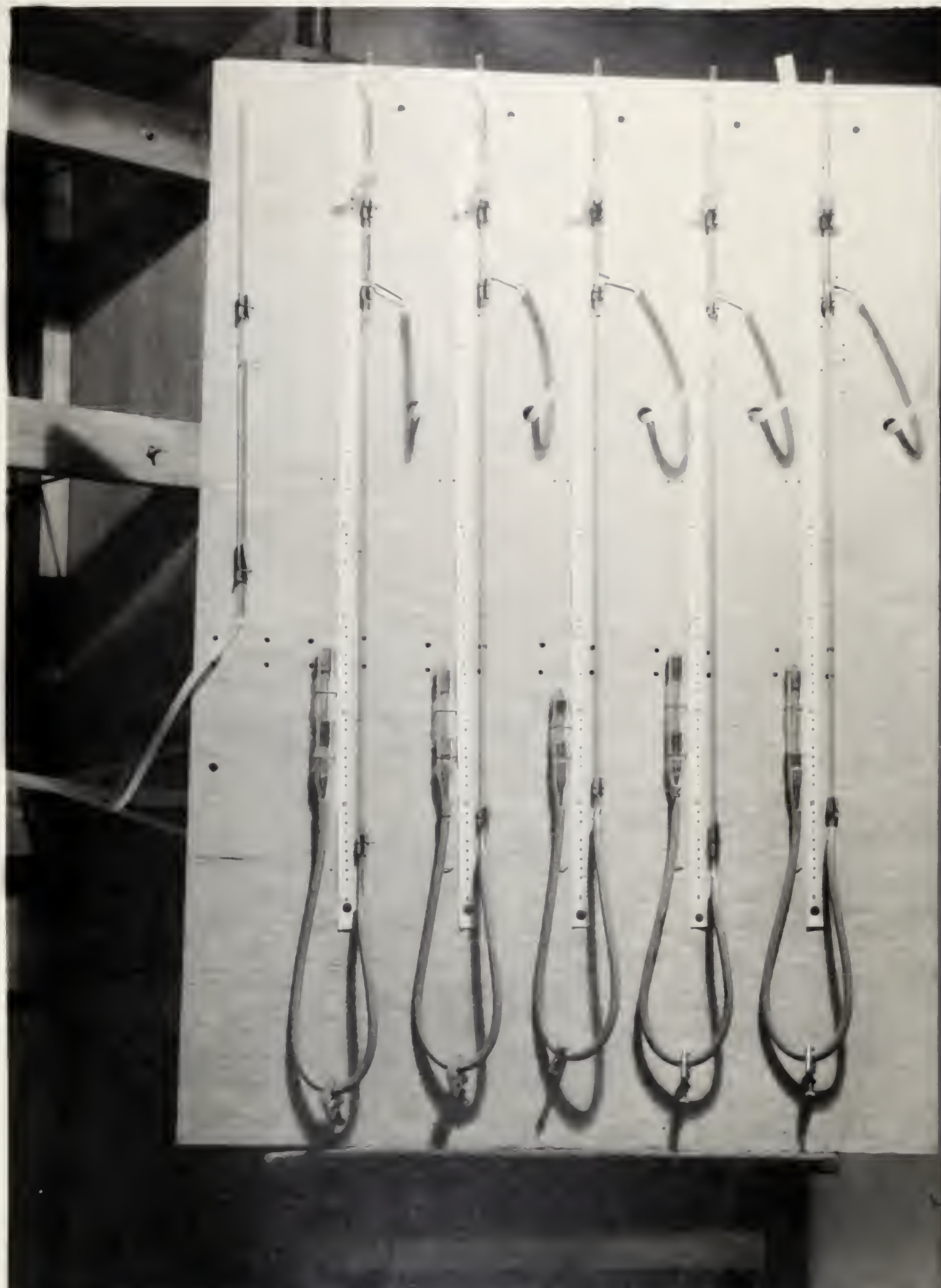


PLATE 12

MANOMETER BOARD

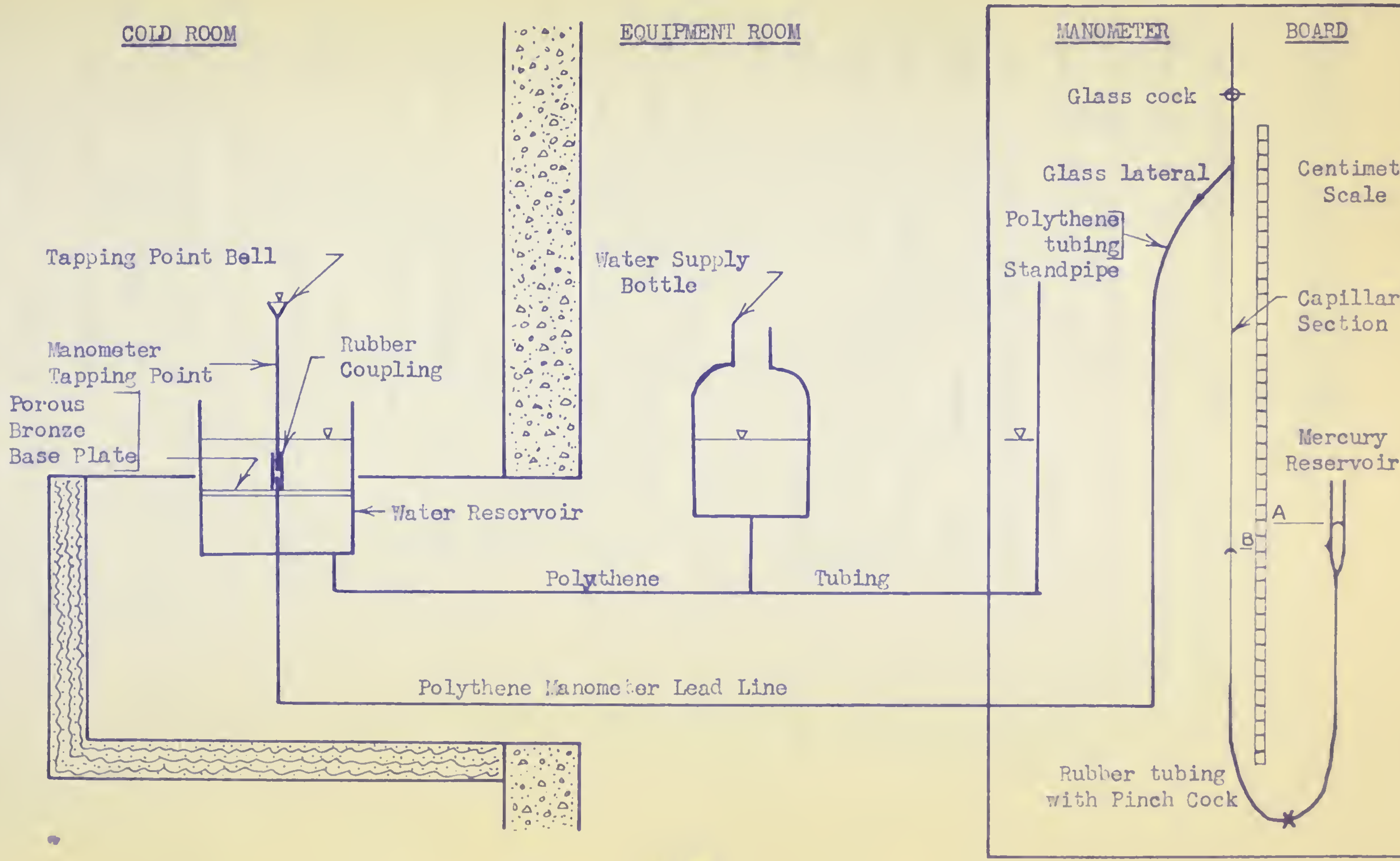


PLATE 13

Schematic Diagram of Test Apparatus

<u>Filling and De-airing the Manometers</u>

The mercury was forced up the capillary tube to the throat of the lateral where it was held by closing the pinch cock on the rubber tube between the mercury reservoir and the capillary section. If the tapping points and rubber couplings were in place, as shown in Plat 14, these were removed. This left the stub ends from the manometer leads sticking up past the porous bronze plate. De-aired distilled water was added until the manometer leads were flooded and the water level in the reservoir was well above them. Vacuum from a water trapped source was connected above the glass cock on the manometer board. The cock was turned on until no air bubbles showed in the water flowing toward the vacuum supply. A visual check was possible as all parts of the manometer involved were either glass or semi-transparent polythene. After closing the glass cock, the vacuum supply was removed and the pinch cock was slowly released, allowing the mercury surface to settle back into the capillary section, drawing water in behind it. The rubber couplings were replaced and de-airing of the tapping points was commenced. This consisted of boiling them in water and then forcing water back and forth through the roll of screen in the throat until no air bubbles were obvious. With the tapping point still submerged, both ends were stoppered and it was lifted out and taken to the water reservoir where the bottom end was submerged and the stopper removed. That end was pushed into the submerged rubber coupling and the stopper was removed from the top, completing the de-airing of the manometer.

In Test 9 the tapping points were not de-aired separately. The vacuum drew water right from the tapping point bell rather than

from the water reservoir. Due to the resistance to flow offered by the roll of screen in the tapping point throat, it was difficult to obtain a strong flow of water, even at vacuums approaching one atmosphere.

In changing from one test to the next, only the tapping points had to be de-aired again. If frozen in for a sufficient length of time they would be pulled right out of the rubber couplings by the heaving of the sample.

Preparation of Frost Heave Test Specimens

Samples were wetted down with de-aired distilled water. With the silt, the moisture content was increased to something greater than the liquid limit of the material and then the sample was allowed to soak for at least twenty four hours before being placed in the frost cell. The gravel samples were not allowed any appreciable soaking time.

The water supply system and manometers were charged and de-aired as explained previously. The water level was lowered until it was flush with the top of the porous bronze plate. This elevation was marked on the panel in the equipment room by the water level stand pipe. From then on water levels were gaged from that mark.

A quarter of an inch of fine sand was placed above the screens in the tapping points to act as a filter. This sand was de-aired by boiling. It was then transferred to the tapping point bells which were full of water. With the free water surface at the top of the bell, the initial or zero readings on the manometers were recorded. In Test 9 the level of the mercury in the reservoir branch and that

in the capillary section were recorded. In the other tests the diameter of the reservoir was large compared to that of the capillary tube so that only the elevation of the mercury surface in the capillary tube was recorded. The thermocouples were strung into the frost cabinet and threaded into the holder, as shown in Plate 14.

The first three rings of the sample container were set on the porous bronze plate and the reservoir cap was placed to hold the rings in position. The sample was then placed, using a rapid tamping motion with a one quarter inch diameter rod to push the material around the rubber couplings and manometer tapping point stems. After the first three, rings were added one at a time and filled in a similar manner. When the level of the sample came up to the top rim of a tapping point the free water was taken down to the sand filter and the specimen material was tamped inside the bell. This procedure was continued until the specimen was complete.

The thermocouples were pushed about half an inch into the sample through the holes in the rings provided for that purpose. The extensometer was brought into contact with a cover plate on the sample and the initial reading was taken. Loose insulation was placed level with the top of the test specimen. De-aired distilled water was added to the water supply bottle until the level in the stand pipe indicated that the water level was at the required height above the porous bronze plate. The temperature recorder, circulation fans and cooling unit were started and the starting time was recorded. The frequency of taking readings varied. Generally, all readings were taken once an hour during the day and not at all during the night, except for temperatures which

PLATE 14

MANOMETER TAPPING POINTS

were recorded continuously.

Freezing of Samples

Samples were frozen until the frost line was in the vicinity of the highest manometer tapping point, at which time they were allowed to thaw. This procedure was followed in tests 9, 10, 11, 12 and 13, with the exception of test 11 which thawed considerably during test due to a power failure. Tests 12A-12F and 13A-13C are refreeze tests on the samples from tests 12 and 13, respectively. Samples were completely thawed and the sample container rings were reseated before each refreeze test. In test 13, insulation was removed from around the upper end of the specimen to force the frost line down; in other tests either the temperature in the cold room was lowered or sufficient time was allowed for the frost line to penetrate under constant room temperature. Plate 15 is a photograph of the specimen from test 13 with the insulation taken away while it was still frozen.

PLATE 15

FROZEN SPECIMEN

CHAPTER V

RESULTS AND DISCUSSION

Sample Materials

The materials used in the frost heave tests were a silt and two gravels. The data and results of classification tests on these materials are included in Appendix B. The grain size curves are on Plate 16, and the pressure-void ratio curve for the silt is on Plate 17.

The following is a summary of the results of these tests on the silt material.

A. Atterberg Limits	
1. Liquid limit	25.2%
2. Plastic limit	21.5%
3. Plasticity index	3.7%
B. Hydrometer Analysis	
1. Sand sizes[1]	30%
2. Silt sizes	62%
3. Clay sizes	8%
4. D_{10} size (mm.)	0.003
5. Uniformity coefficient	10
C. Consolidation Test	
1. Compressive index	0.066
2. Permeability (cm./sec.)[2] . . .	10^{-8}
D. Capillarity (cm. of water)	605

The grain size curve indicates that the material is a well graded silt. The Atterberg limits indicate slight plasticity. On a plasticity chart, the material classified as an "ML" which includes inorganic silts, rock flour, etc.[3]. Table XV, Appendix B, is a

---

[1] Grain sizes are according to the Massachusetts Institute of Technology grain size scale.

[2] Approximate order of values computed from consolidation test results for a remolded specimen.

[3] Arthur Casagrande, Classification and Identification of Soils, American Society of Civil Engineers, Trans., Vol. 113, 1948, p. 910.

UNIVERSITY of ALBERTA
DEPT. of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY
GRAIN SIZE CURVE

PROJECT	45
SITE	
SAMPLE	
LOCATION	
HOLE	DEPTH
TECHNICIAN	DATE

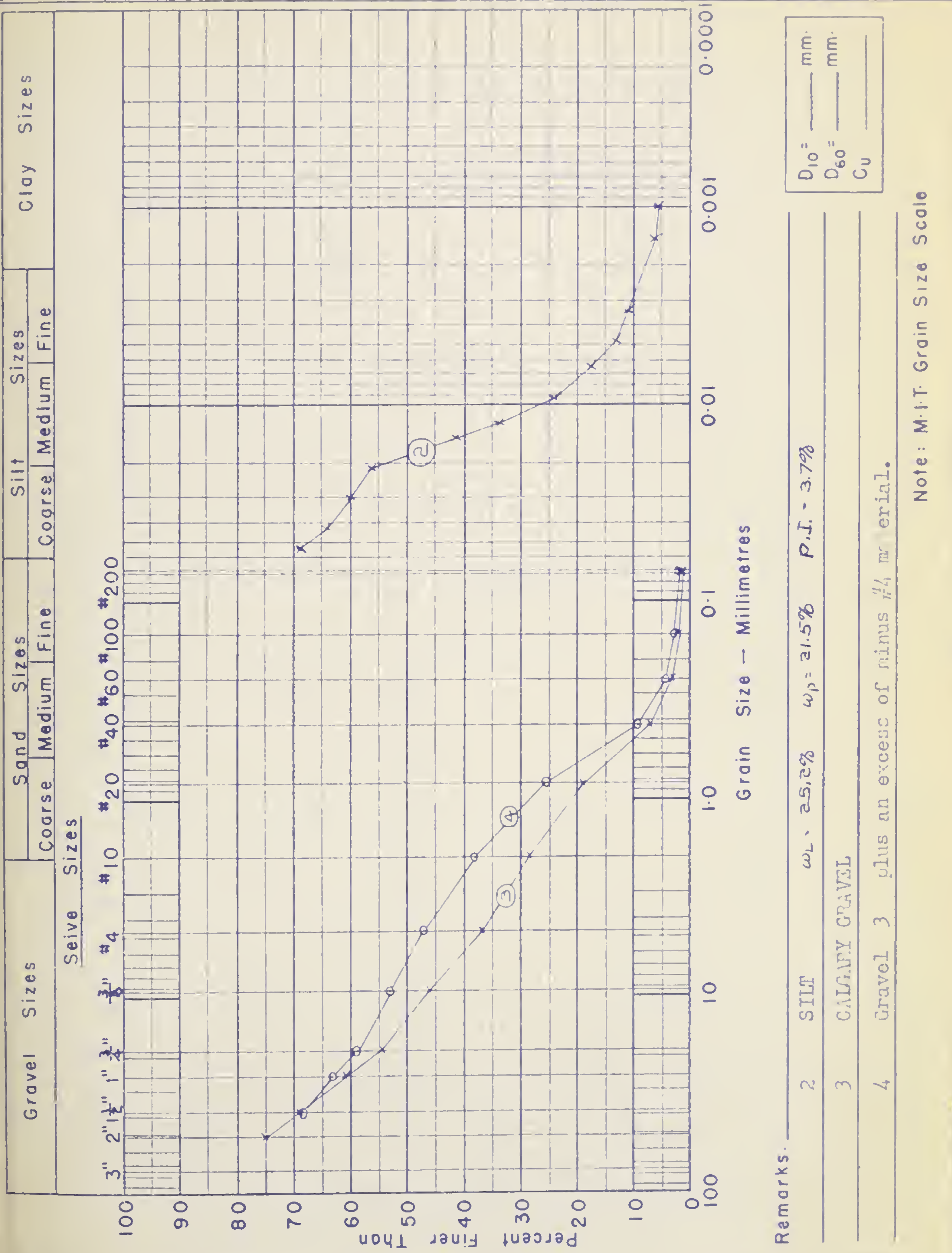


PLATE 16

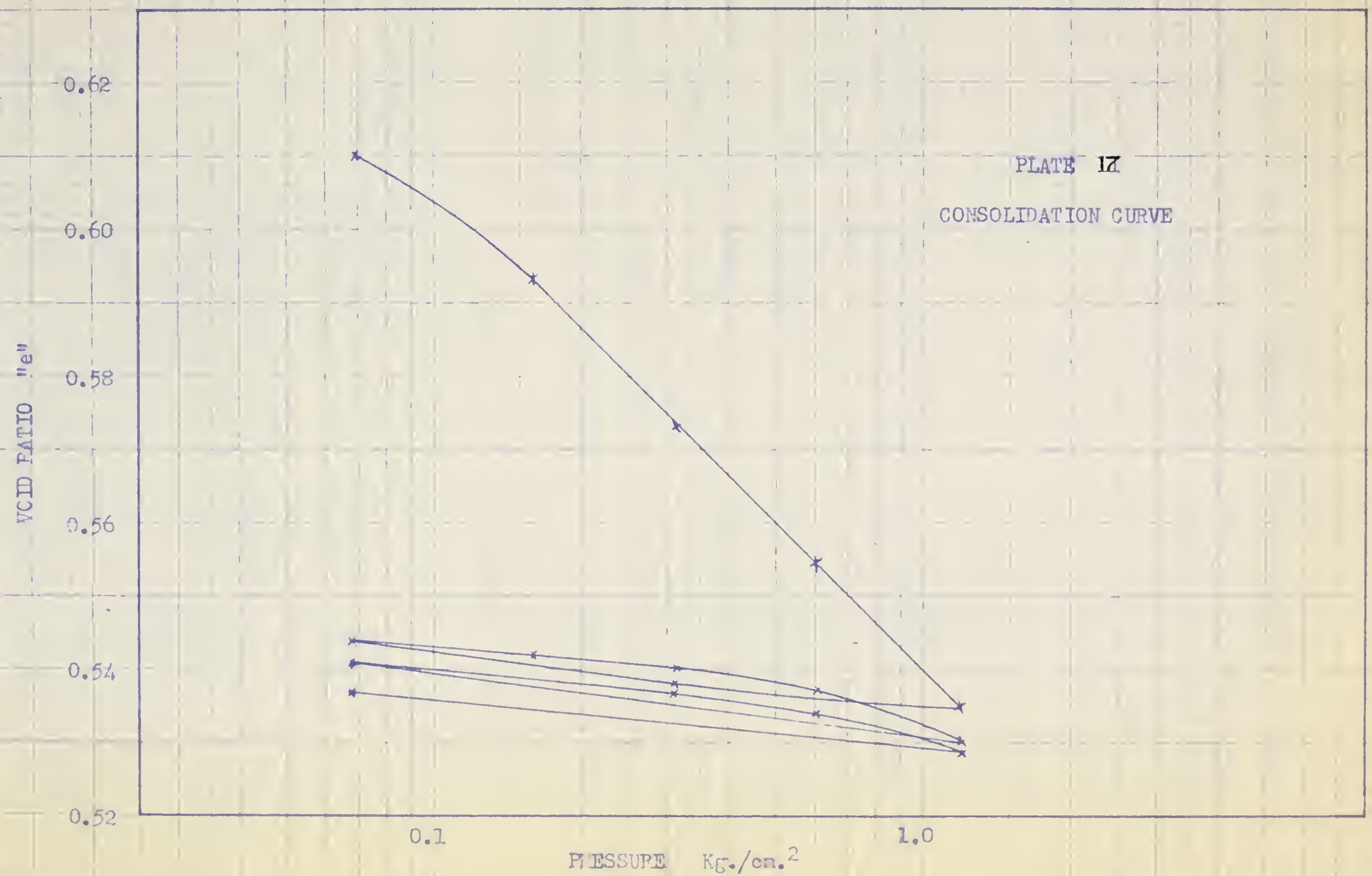


PLATE IV
CONSOLIDATION CURVE
0.62
0.60
0.58
0.56
0.54
0.52
VOID RATIO "e"
0.1
1.0
PRESSURE Kg./cm.^{2}

summary of permeability computations. These were computed for four increments of pressure between 0.069 and 1.18 kg./cm.^{2}. The average void ratio in individual increments varied from 0.60 to 0.54 and the permeability values ranged from 2.4×10^{-7} to 2.0×10^{-7} cm./sec., for the first loading cycle. The corresponding void ratio variation, for the first reloading cycle was 0.54 to 0.53; for the second it was the same, to two significant figures. For the first loading cycle, the permeability at the higher void ratio was 1.2 times that at the lower void ratio. This factor, for the reloading cycles (determined using equation (II.15)), is 1.05. These results are based on a consolidation test on a specimen consisting of the silt material used in the testing program. As the consolidation specimen was molded at a moisture content approximately the same as that at which the frost heave, specimens were formed, it is proposed that as an approximation the consolidation results can be applied to the frost heave specimens, within the range of pressures indicated.

The following is a summary of the sieve analysis results for the gravels.

A. Calgary Gravel
   1. Gravel sizes . . . 72%
   2. Sand sizes 27%
   3. Finer than sand . . . 1%
   4. D_{10} . . . . . . 0.5 mm
   5. Uniformity coefficient . . 50

B. Calgary Gravel (with excess of material passing No.4 sieve)
   1. Gravel sizes 62%
   2. Sand sizes 36.5%
   3. Finer than sand . . . 1.5%
   4. D_{10} . . . . 0.4 mm
   5. Uniformity coefficient . . 43

Both of these gravels classify as "gravels with fines" (GF) according to the Airfield Classification System, and as "coarse material with fines" (A-2), using the Public Roads Classification. The Casagrande

criterion for frost susceptibility in a well graded material is that the fraction finer than 0.02 mm. shall be in excess of three percent (7). On this basis neither of these gravels should be frost susceptible.

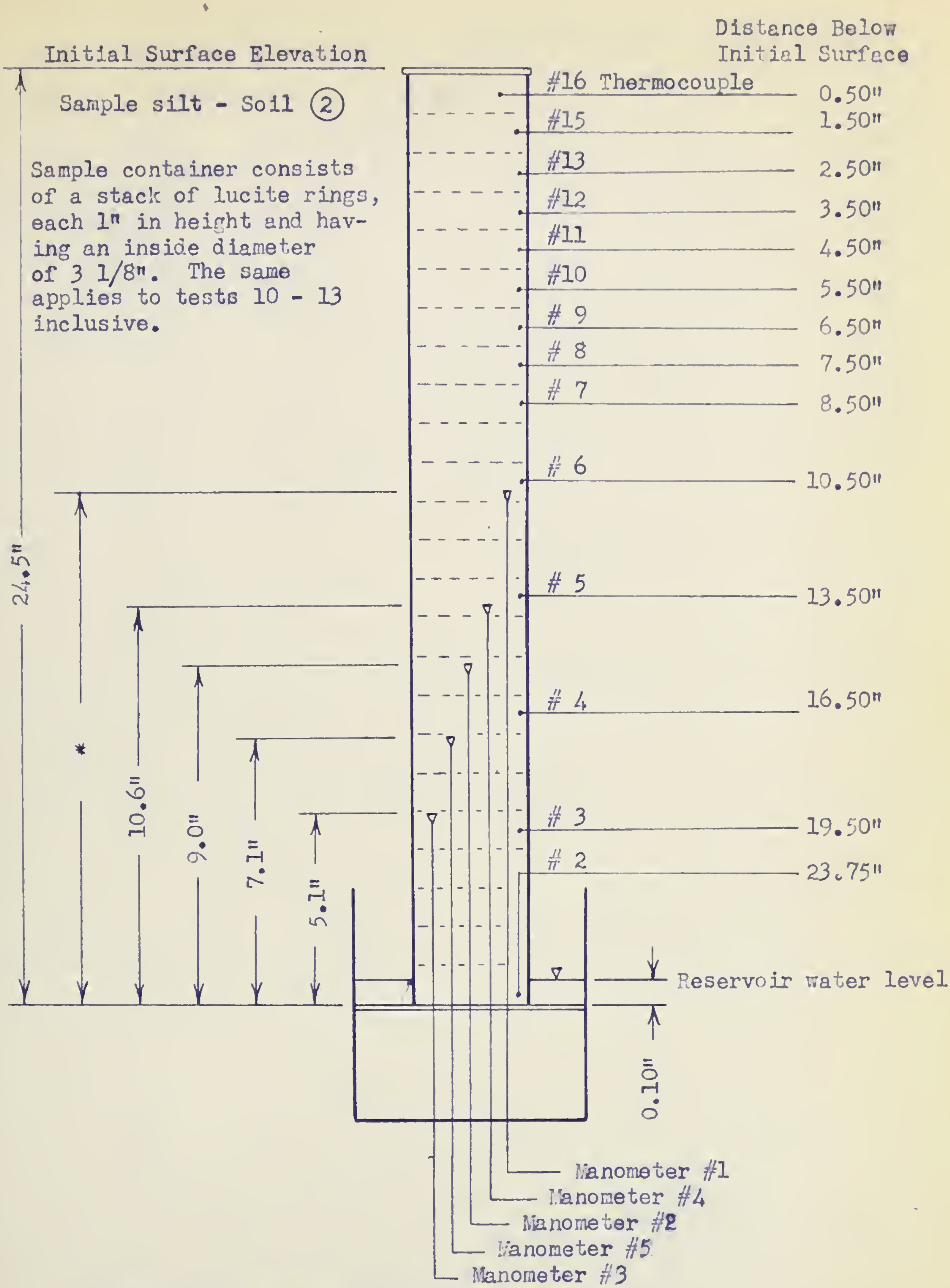
Specimen Data

In this investigation five specimens were instrumented and subjected to freezing. Three were silt specimens having different lengths and two consisted of gravel overlying the same silt. Specimen data and details of the instrumentation are given in Plates 18A to 18D. The designation used for thermocouples and manometers corresponds with that used on the original data sheets. The lengths giving the locations of thermocouples and manometer tapping points are accurate to $\pm$ 0.05 inches.

Frost Heave Test Data and Initial Computations

The quantities measured during the frost heave tests consisted of the elevation of the top surface of the specimen relative to an arbitrary datum, the elevation of the water-mercury interface in each manometer, the time, and the temperature at various intervals throughout the length of the specimen.

Top surface elevation was determined by means of an extensometer as shown in Plate 15. This was set and read before temperature was dropped. Subsequent readings indicated that the surface dropped slightly before starting a prolonged rise. The initial drop is attributed to the difference in contraction between the sample container and the stand supporting the extensometer. The minimum reading was taken as the initial value. The difference between this and later readings was



* Manometer #1 was inoperative in this test.

PLATE 18A

DETAILS OF INSTRUMENTATION
FOR TEST 9

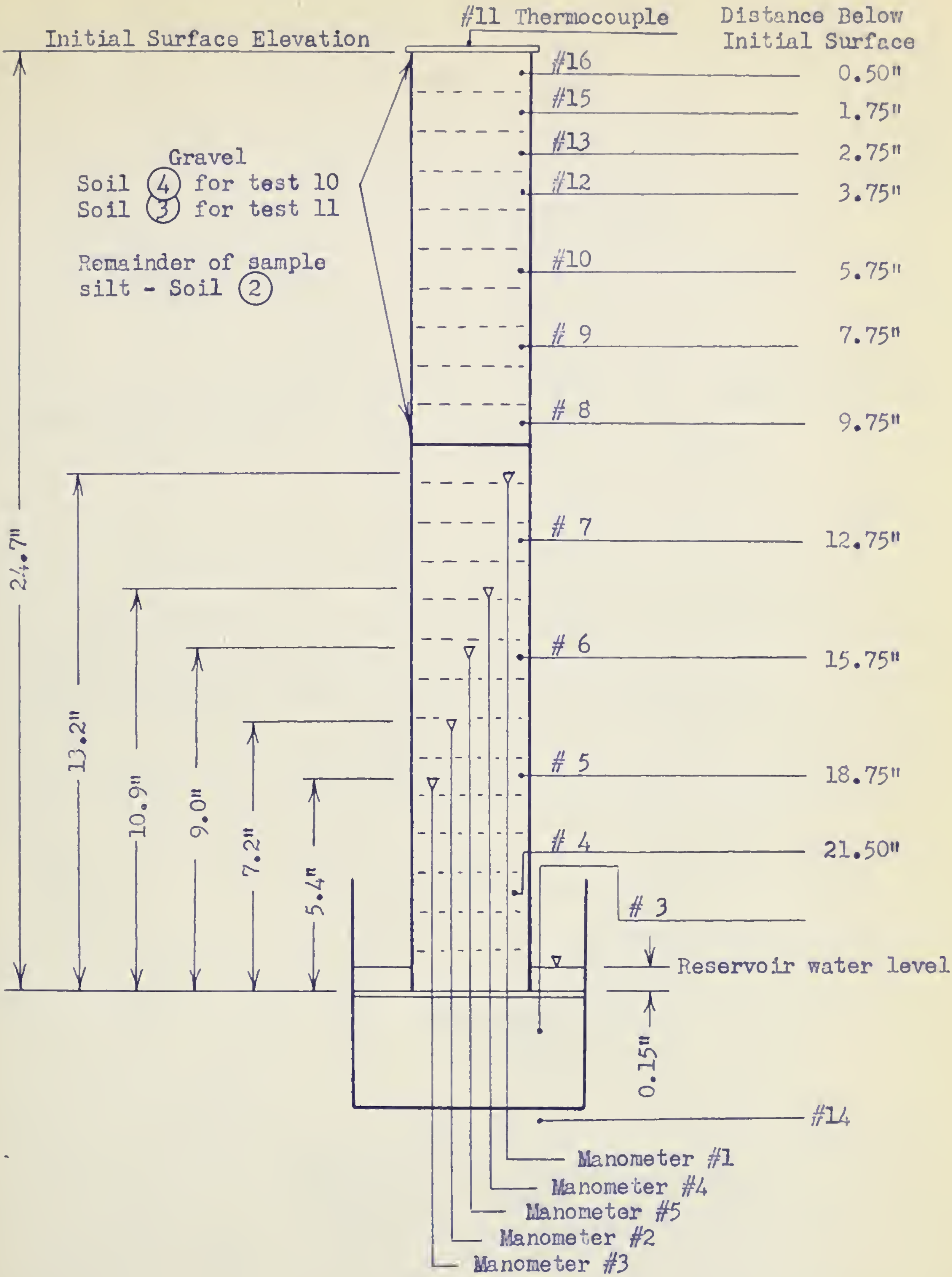


PLATE 18 B

DETAILS OF INSTRUMENTATION
FOR TESTS 10 AND 11

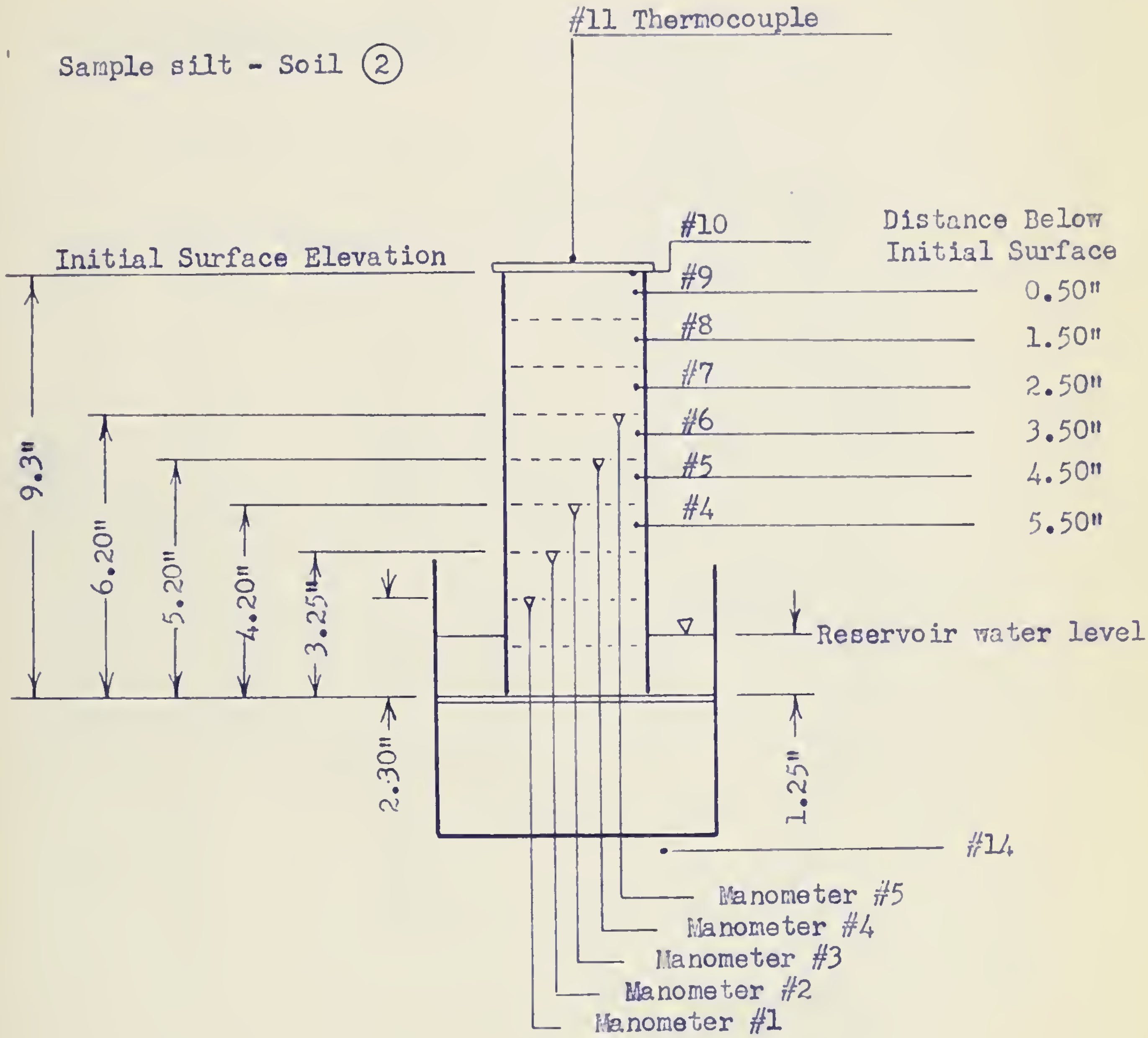


PLATE 18C

DETAILS OF INSTRUMENTATION
FOR TEST 12-12F

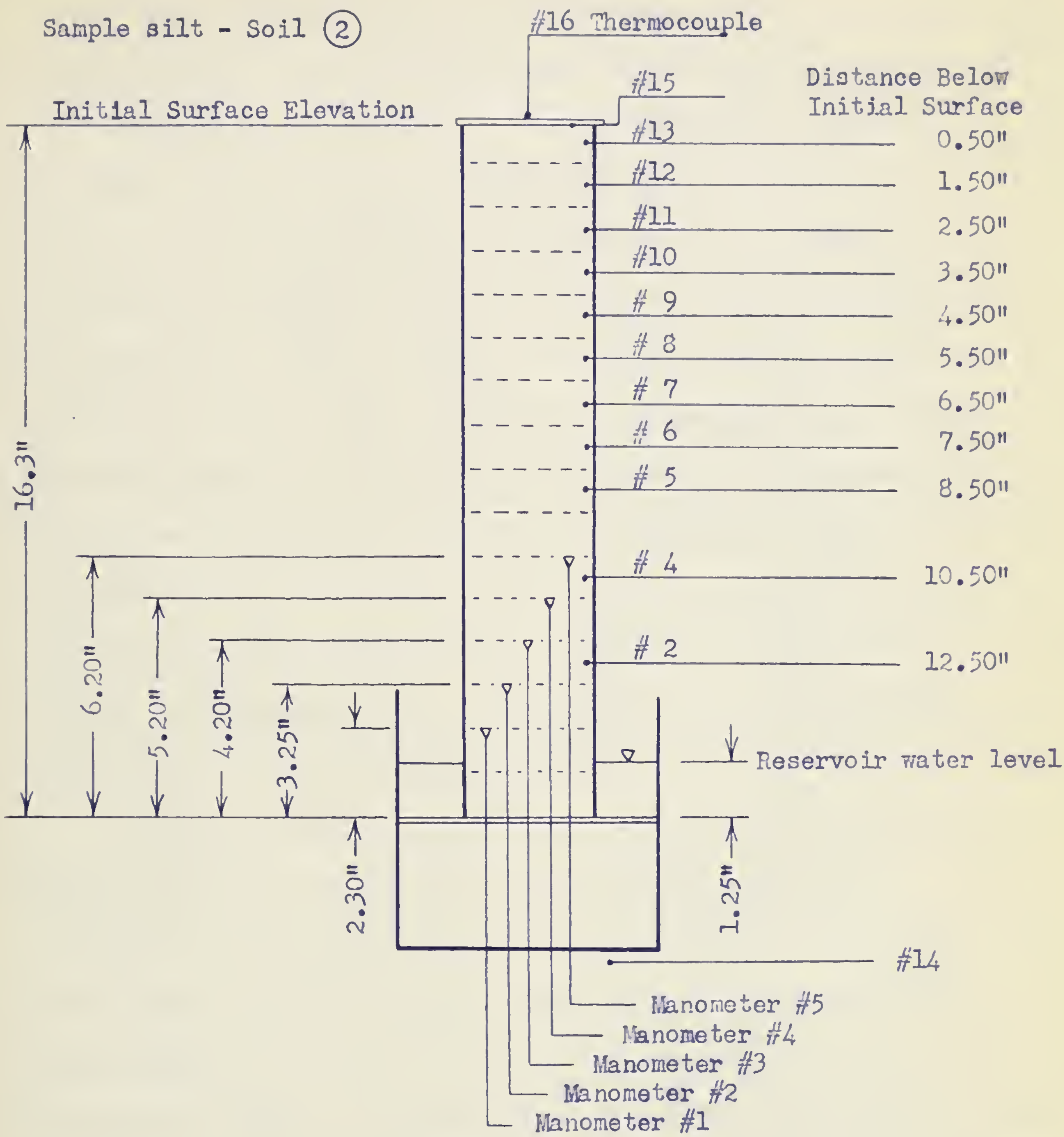


PLATE 18D

DETAILS OF INSTRUMENTATION
FOR TEST 13-13C

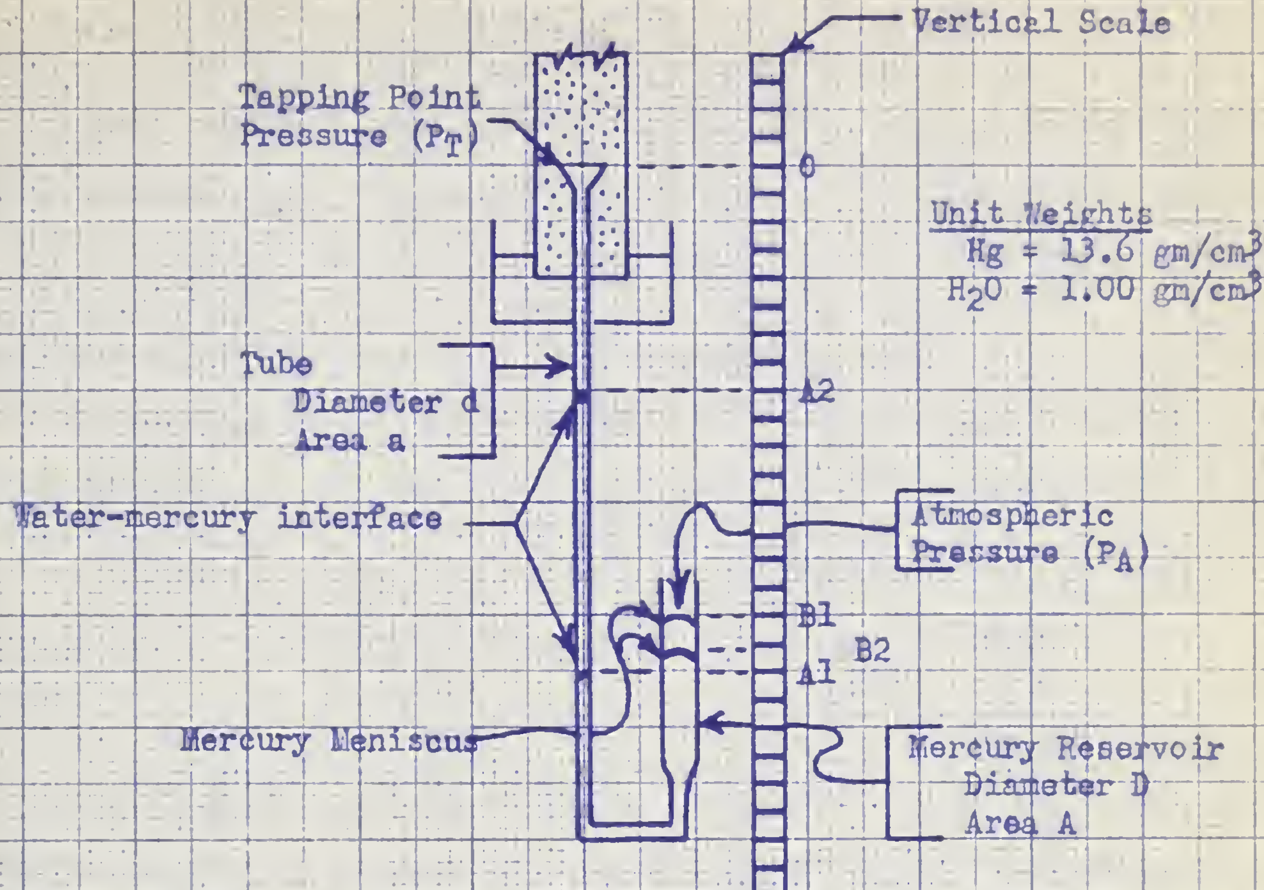
taken as the total heave.

Water-mercury interface elevations were read directly from centimeter tapes on the manometer board. The elevation corresponding to atmospheric pressure was determined as outlined in Chapter IV. The difference between the initial and subsequent elevations was used to determine the pressure at each tapping point. The method used for determining pressures is shown on Plate 19. These quantities were expressed in "cm. of water" but would be numerically the same, if expressed in the units "gm./cm.^{2}". The first units correspond to "pressure energy" or "pressure head" in fluid mechanics terminology. With the second units, the quantities correspond to "pressure" in fluid mechanics, and "neutral pressure" in soil mechanics. In any case, the pressure in the fluid at a particular tapping point, relative to atmospheric pressure, is specified. These quantities will be called "piezometric pressures".

In determining the elapsed time from the start of test, zero time was taken at the instant the cooling unit was started.

By the process of interpolation, the position of the 32°F. isotherm was determined. It was assumed that the distance between thermocouples was the same as measured before the start of the test and that the temperature gradient was constant between the thermocouples considered. The frost line was considered to exist at the location of the 32°F. isotherm.

All the original data is on file with the Department of Civil Engineering, University of Alberta, along with quantities computed directly from that data.



Let A1 and A2 represent the positions of the mercury surfaces when $P_T = P_A$. It follows that

$$P_T = P_A = (B1 - A1)13.6 - (C - A1)1.00 + P_A \quad . \quad . \quad (1)$$

If the mercury is at A2 and B2 for P_T less than P_A, P_T is given by

$$P_T = P_A - (A2 - B2)13.6 - (C - A2)1.00 \quad . \quad . \quad . \quad (2)$$

Subtracting equations (1) and (2), we get the equation for difference in pressure which was used in the computations for Test 9.

$$P_T - P_A = -(A2 - A1)13.6 - (B1 - B2)13.6 + (A2 - A1)1.00 \quad (3)$$

or $$P_T - P_A = \Delta P = -(A2 - A1)12.6 - (B1 - B2)13.6$$

By substituting $(B1 - B2) = (A2 - A1)a/A$, we get

$$\Delta P = -(A2 - A1)12.6 - (A2 - A1)13.6\ a/A \quad (4)$$

In Tests 10 to 13, a/A = 0.006, so that the error involved in dropping the last term in equation (4) is less than one percent.

PLATE 19

PIEZOMETRIC PRESSURE DETERMINATION

A General Consideration of Frost Heave Test Results

Heave, depth of frost line and piezometric pressures have been plotted as functions of time, on Plates 20A to 20E. The plots present an overall picture of the behavior of these quantities throughout each test.

During the course of freezing, negative pressures developed in the pore water. In certain instances the pressure values were subject to fluctuations. In Tests 9 and 11 where the cold room temperature was held constant for extended periods of time, the fluctuations were most pronounced. Test 9 from 320 and 780 hours illustrates the course of events following a drop in the cold room temperature. Three stages can be identified. In the first, heave, depth of frost line and piezometric pressure increase relatively rapidly. Second, values seem to oscillate about a steadily increasing average. The third stage is characterized by unpredictable fluctuations terminating with a near static frost line, much reduced piezometric pressures and very little heave. The conditions in this stage seem to be approaching equilibrium for the temperatures imposed. Under conditions where the average applied freezing temperature decreased slowly and steadily, it would be expected that stage one and three would not exist. Therefore stage two conditions would be expected to exist in the field where the frost line is not affected by daily air temperature fluctuation. When, over a period of time, the fluctuating quantities can be represented by increasing straight lines, the conditions would appear to be steady, with the average heave, depth of frost line and piezometric pressures all increasing.

An increase in the depth of the frost line will result in a shorter path from the reservoir and a larger surcharge at the frost line. It has been shown by Beskow (6) that the rate of heave varies inversely as the effective pressure at the frost line; the effective pressure being equal to the negative pore pressure plus the surcharge. Therefore, the dropping frost line results in factors whose effects on the rate of heave tend to be compensating. Increasing negative stresses within the specimen will result in increasing average hydraulic gradients (the piezometric pressure at the water reservoir being constant) and increasing effective pressures at the frost line. These factors will tend to produce opposite effects in the rate of heave, assuming that the flow is governed by Darcy's law. For unsaturated conditions and steady flow, the effect on the rate of heave of increasing the hydraulic gradient will be opposed by a corresponding decrease in the permeability. The indications are that while there are variations in a number of factors during the freezing process, the changes in individual factors have opposite effects on the rate of heave. For a constant rate of heave the net effect is zero. This situation is approached on an average value basis, by the conditions in stage two (described previously).

According to the "fluctuating frost line" theory of Benkleman and Ohmstead (23), an oscillating frost line is a prerequisite to ice segregation. Results indicate that fluctuation of the frost line is but one of the consequences of ice segregation. The Benkleman and Ohmstead theory assumed that the frost line would rise and fall with the surface temperature. While this may well be true, test results

show that the frost line can fluctuate while the end temperatures are held constant. It appears that the same situation would exist for slowly falling surface temperatures.

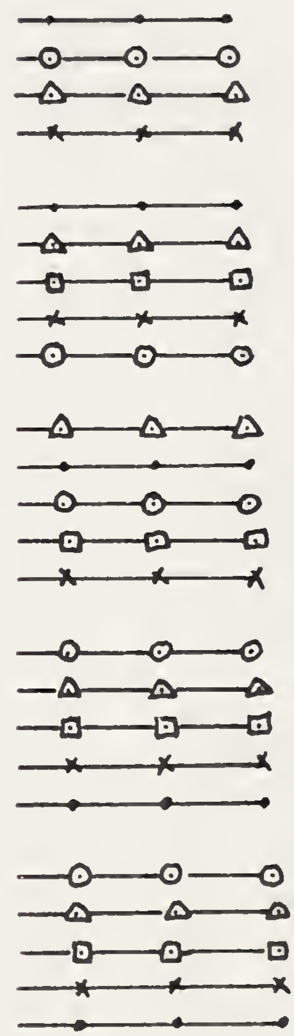
According to the "rhythmic ice banding" theory of Martin (24), ". . . the problem involves the interrelationship of (a) the phase change (liquid to solid), (b) the mass transport of liquid to the freezing front, and (c) the condition of a general unsteady heat flow found in a freezing soil." He goes on to explain the cyclic nature of ice segregation. "Nucleation of ice" represents the start of a new lens. This takes place below the existing frost line. Nucleation is followed by a period of rapid crystal growth, after which the growth terminates. Subsequently the cycle repeats. The physical conditions during this cycle, were explained by Martin as follows. Nucleation takes place at some temperature lower than the normal freezing temperature of the liquid. The rapid growth following nucleation involves the freezing of the "free" water which is immediately available. This is accompanied by a rapid release of heat at the growing crystal and by the depletion of the moisture in the vicinity. The latter factor results in increasing negative stresses in the pore fluid and lowers the freezing point temperature. The net effect of the various factors is to reduce the rate of crystal growth. Eventually the temperatures below become depressed to a point where nucleation occurs and the whole cycle repeats. It would appear that the fluctuations in heave, depth of frost line and piezometric pressure values observed in the frost heave tests can be explained in terms of the "rhythmic ice banding" theory.

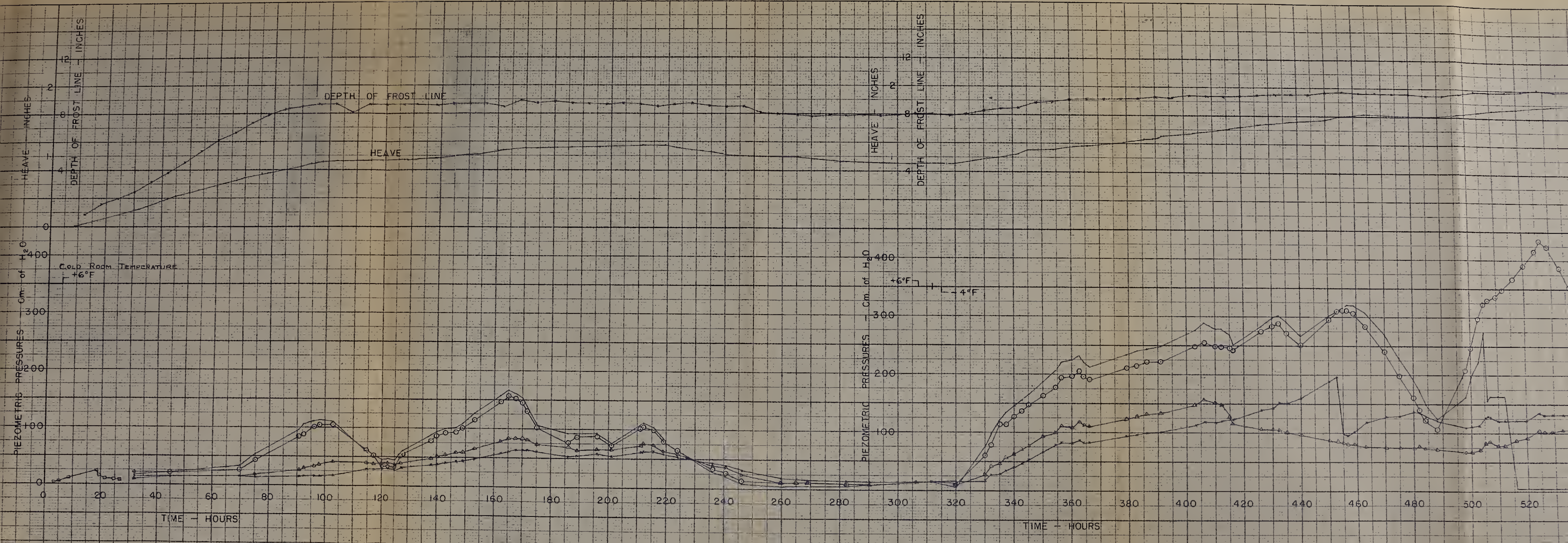
On the basis of laboratory tests using an apparatus in which

the formation of ice lenses could be observed, Daxelhofer (25) concluded that "The formation of successive ice lenses appears to depend on thermal variations which bring about thawing at the boundary of the frozen zone . . ." This hypothesis differs from the theory of Benkleman and Ohmstead in that the thermal variations are not attributed to variations in the applied temperatures. Martin does not include thawing as part of the cycle in the "rhythmic ice banding" theory, although thermal variations are recognized as "the condition of general unsteady heat flow". The most obvious thawing that occurred during the present investigation, took place when the average rate of heave and the average rate of penetration of the frost line were approximately zero. Thus, thawing and refreezing at the frost boundary does not necessarily result in the formation of an ice lens. In other cases where the piezometric pressures were fluctuating the rate of penetration of the frost line appeared to approach zero at the peak of the oscillations but in most cases there was no indication of thawing. However, the position of the frost line was determined by an interpolation in which it was assumed that the distance between thermocouples was the same as at the time they were placed and that the temperature gradient was constant over the interval interpolated. It is possible that these assumptions could have introduced sufficient error to mask minor thawing in the specimen.

LEGEND FOR PLATES 20A TO 20E

	Tapping Point Elevation Cm.	Designation
Test 9	26.6	
	22.6	
	17.7	
	12.7	
Test 10	33.1	
	27.3	
	22.5	
	17.9	
	13.3	
Test 11	33.1	
	27.3	
	22.5	
	17.9	
	13.3	
Test 12	12.5	
	10.0	
	7.5	
	5.1	
	2.6	
Test 13	12.5	
	10.0	
	7.5	
	5.1	
	2.6	





DEPTH OF FROST LINE
HEAVE
HEAVE - INCHES
DEPTH OF FROST LINE - INCHES
COLD ROOM TEMPERATURE
+6°F
-4°F
PIEZOMETRIC PRESSURES - Cm. of H2O
TIME - HOURS

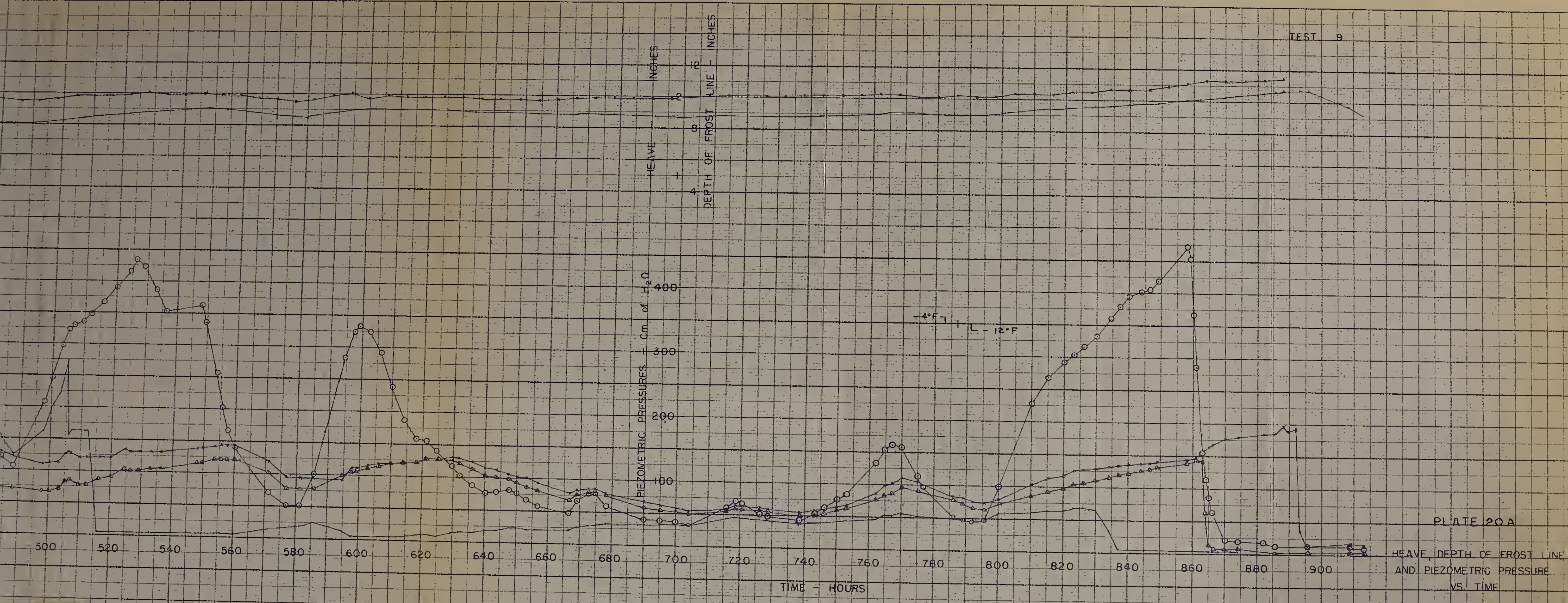


PLATE 20A

HEAVE, DEPTH OF FROST LINE AND PIEZOMETRIC PRESSURE VS. TIME

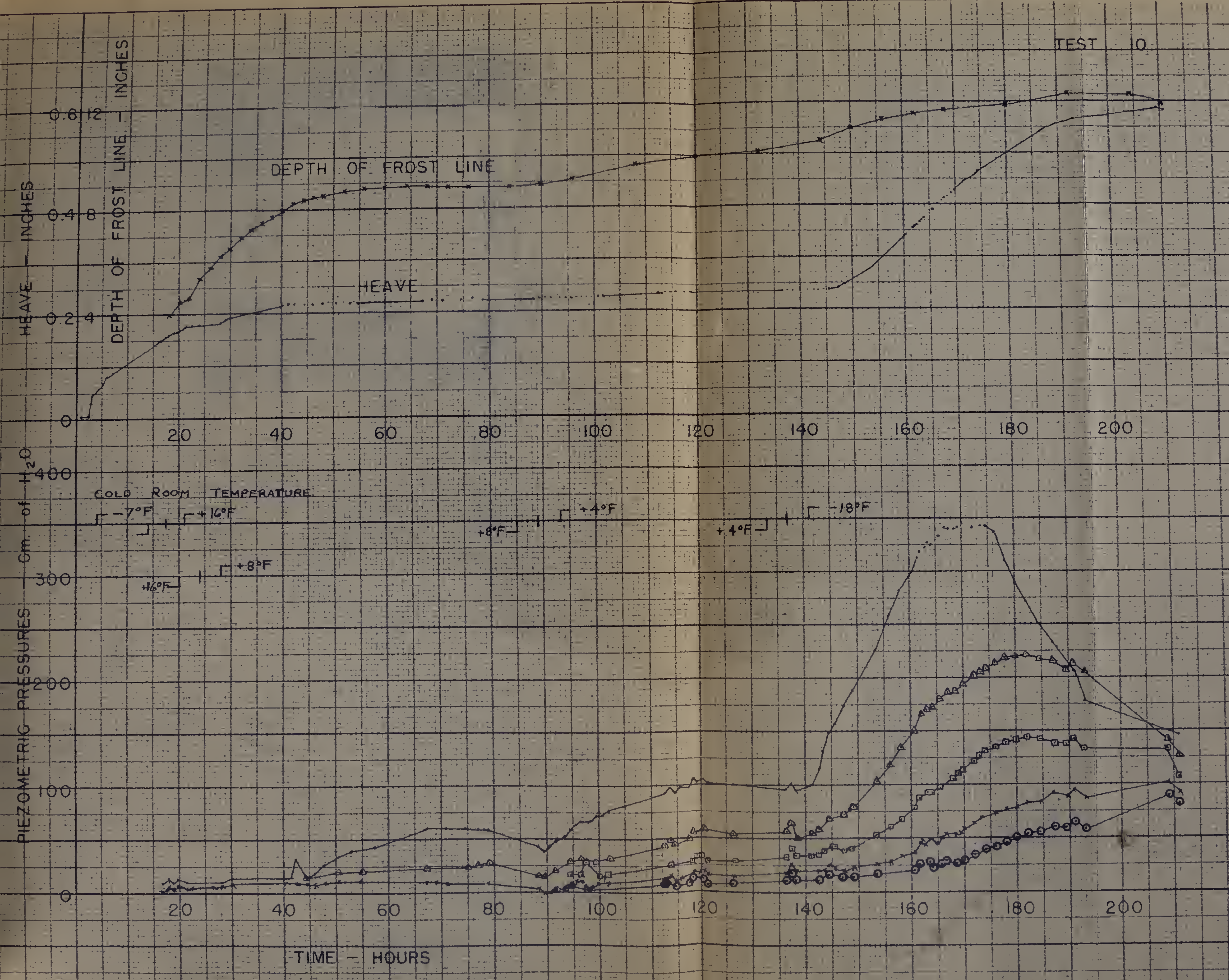
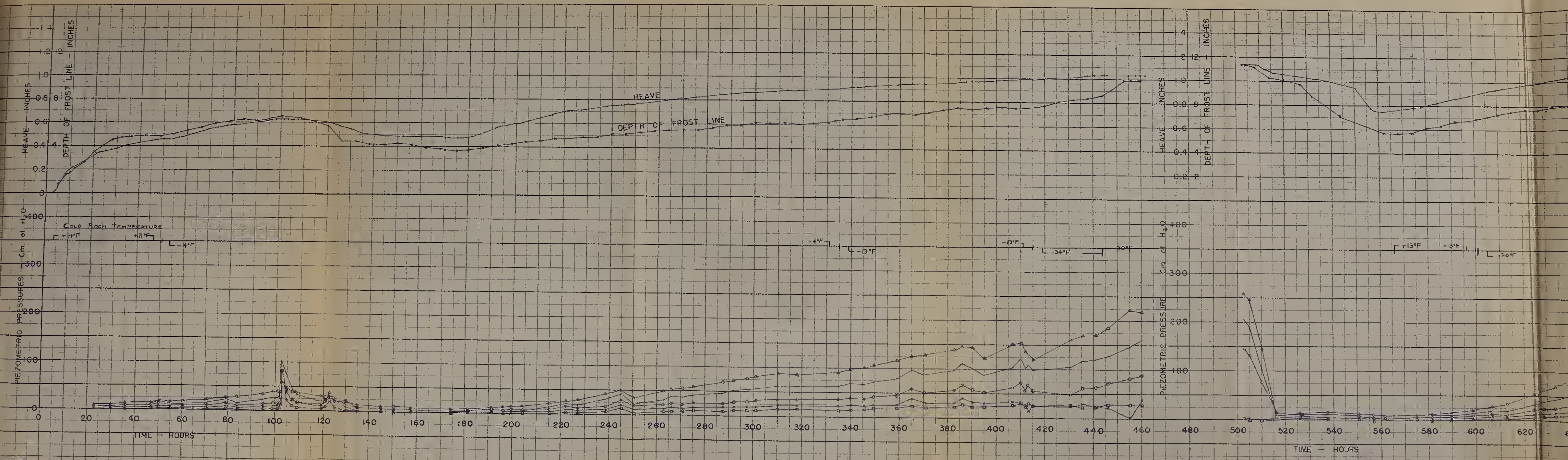


PLATE 20B

HEAVE, DEPTH OF FROST LINE AND PIEZOMETRIC PRESSURE VS TIME


HEAVE - INCHES
DEPTH OF FROST LINE - INCHES
HEAVE
DEPTH OF FROST LINE
COLD ROOM TEMPERATURE
+11°F
-4°F
-13°F
-34°F
-30°F
+13°F
-20°F
PIEZOMETRIC PRESSURES - Cm. of H2O
PIEZOMETRIC PRESSURE - Cm. of H2O
TIME - HOURS

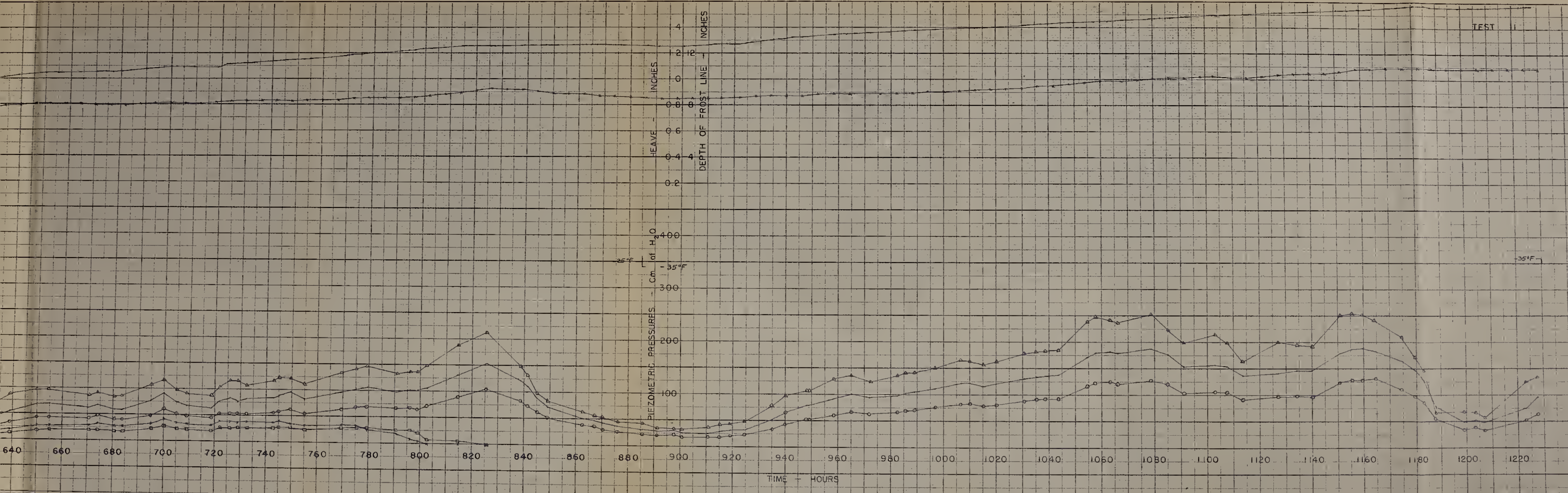
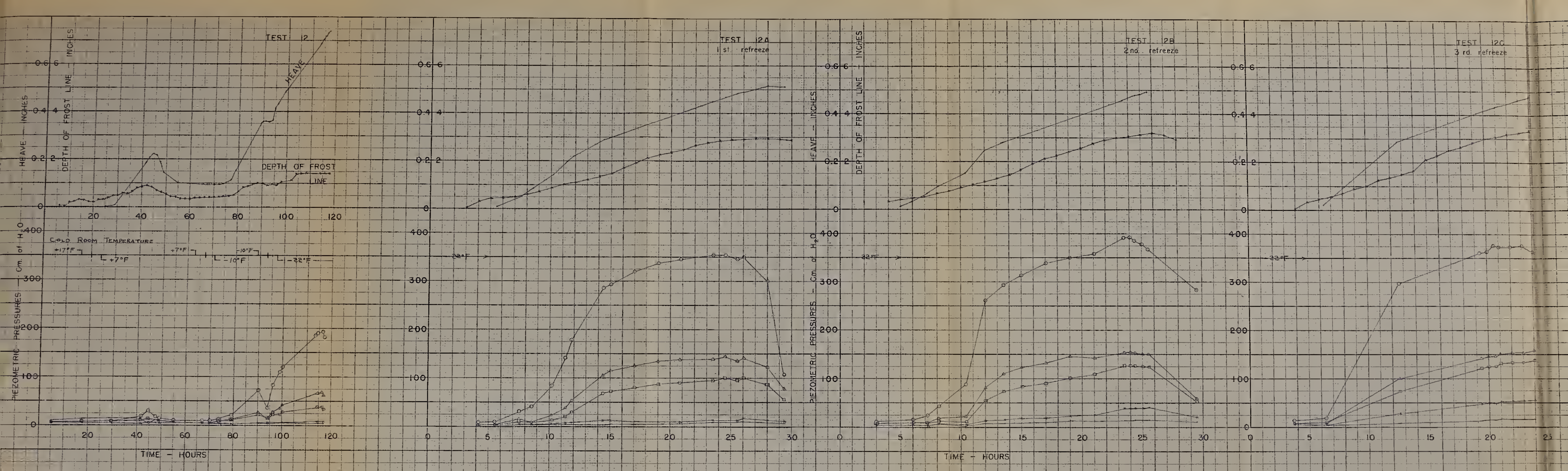


PLATE 20C

HEAVE, DEPTH OF FROST LINE AND PIEZOMETRIC PRESSURE VS. TIME


TEST 12
HEAVE
DEPTH OF FROST LINE
HEAVE - INCHES
DEPTH OF FROST LINE - INCHES
COLD ROOM TEMPERATURE
+17°F
+7°F
+7°F
-10°F
-10°F
-22°F
PIEZOMETRIC PRESSURES - Cm of H2O
TIME - HOURS
TEST 12A
1 st. refreeze
32°F
TEST 12B
2nd. refreeze
TEST 12C
3 rd. refreeze

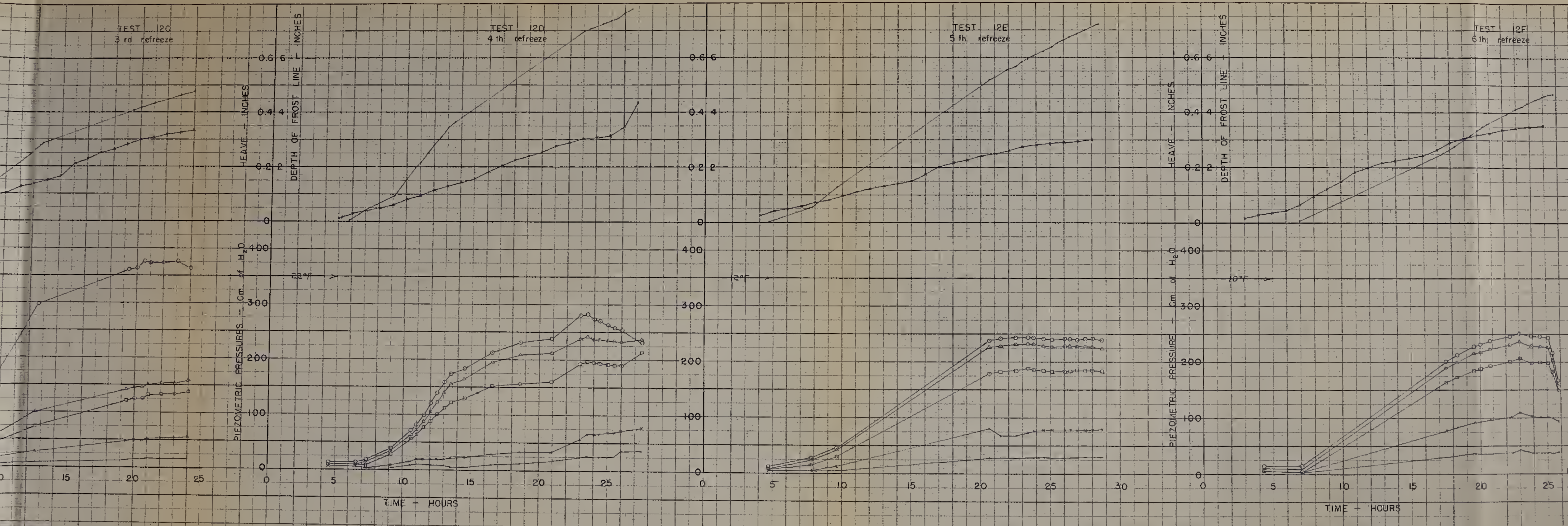
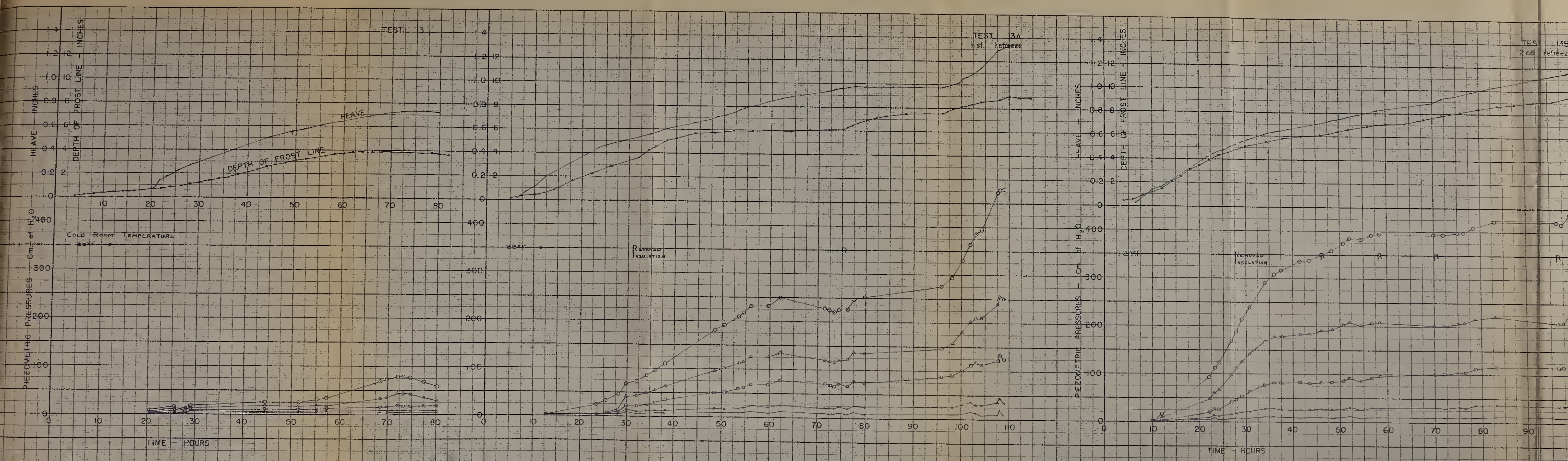


PLATE 20D

HEAVE, DEPTH OF FROST LINE AND PIEZOMETRIC PRESSURE VS. TIME



TEST 3
HEAVE
DEPTH OF FROST LINE
HEAVE - INCHES
DEPTH OF FROST LINE - INCHES
COLD ROOM TEMPERATURE
22°F
PIEZOMETRIC PRESSURES - Cm. of H_2O
TIME - HOURS
TEST 3A
1st. refreeze
REMOVED INSULATION
R
TEST 3B
2nd. refreeze

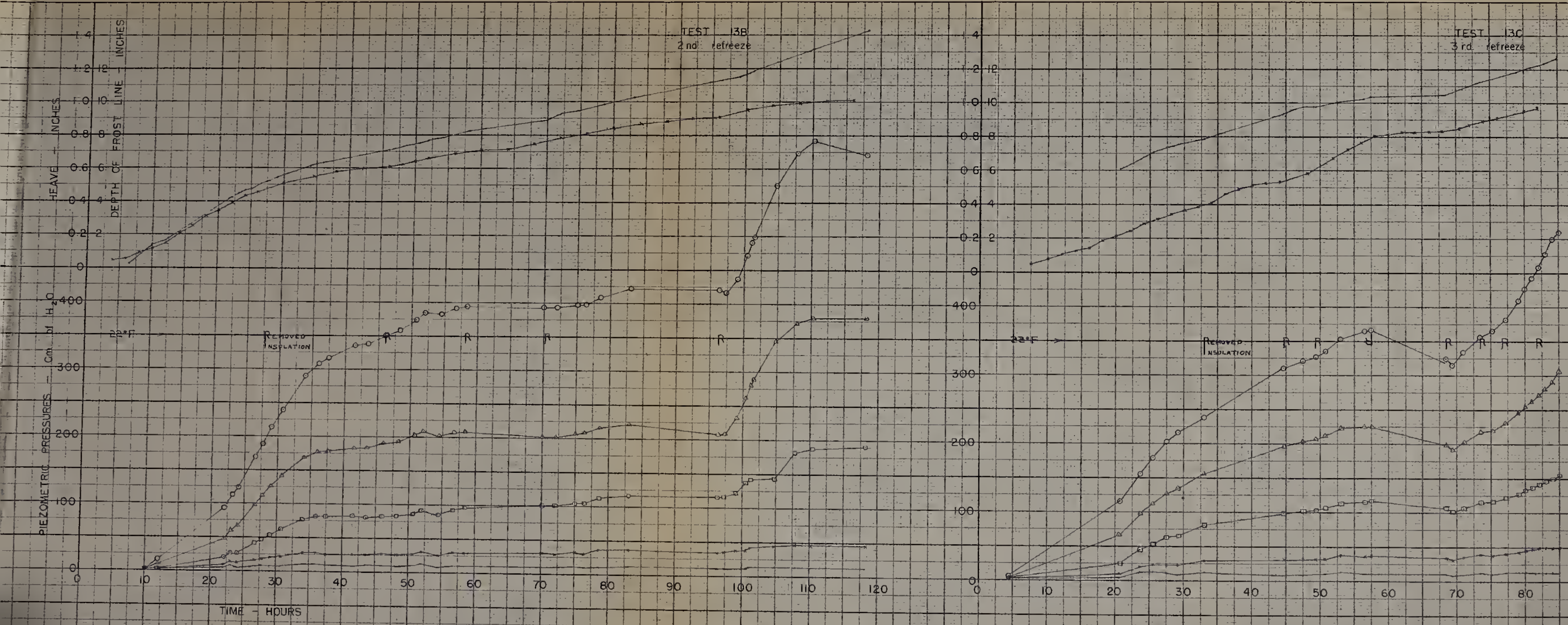


PLATE 20E

HEAVE, DEPTH OF FROST LINE AND PIEZOMETRIC PRESSURE VS. TIME

Analysis of the Pressure Data

The total head (i.e. total energy per unit weight of liquid) values computed using equation (II.1) are listed with the corresponding piezometric pressure values, in Tables III(A) to III(E). Plates 21A to 21J show total head profiles at selected times in the various tests. In the early stages of test the total heads were positive, indicating that there is movement of water downward. These values decreased from the top downward through the sample until total heads were all negative, indicating the movement of water from the water reservoir to the frost line.

The negative total head profiles display curvature of varying degrees. Some curvature is to be expected due to the fact that the viscosity increases along the flow path. Viscosity corrections were made, using equation (II.16) and the method illustrated in Plate 5 (Chapter II).

Tables IV(A) to IV(E) include the temperature data corresponding to each of the total head profiles in Plates 21A to 21J. The temperature profiles (Plates 22A to 22H) were used in conjunction with viscosity-temperature data from the International Critical Tables (Plate 23) to determine the viscosity of the water at each manometer tapping point. One total head profile from each of Test 10, 11, 12B, and 13B was corrected to the viscosity at 20°C. The computations are listed in Table V. Total head profiles in Plate 24 show that for constant viscosity conditions the distribution of total head along the

flow path is non-linear. It remains to investigate the homogeneity of the specimens.

In order to evaluate consolidation effects in the test specimens it is necessary to determine the effective stresses. For the frost heave test specimens the effective stress will be equal to the surcharge due to overlying material and apparatus (a positive quantity) minus the neutral pressure(a negative quantity). The surcharge pressure per unit length of specimen was calculated in Table VI, using estimated values for the void ratio and the degree of saturation. The maximum error due to these assumptions was determined to be $\pm 5\%$. The surcharge pressure at each tapping point is listed in Table VII. Having piezometric pressures and surcharge pressures, the effective pressures were computed (See Tables III(A) to III(E)). The corresponding void ratios were taken from the consolidation curve, Plate 17.

An approximate relationship between permeability and void ratio is given by equation (II.15), $k_1 : k_2 = e_1{}^3/(1 + e_1):e_2{}^3/(1 + e_2)$. For Darcy type flow the permeability may be expressed $k = v/i = Lv/H$ (equation (II.11)). For a particular choice of time and distance along the flow path, v and L are constants, so that k is inversely proportional to the head loss H. Substituting into equation (II.15), we get

$$H_1 = H_2 \left(\frac{e_2{}^3}{(1 + e_2)}\right) \Bigg/ \frac{e_2'{}^3}{1 + e_1} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (V.18)$$

Using this equation and the viscosity corrected total head values,

total head values corrected for both viscosity and void ratio were obtained(See Table VIII). Total head profiles with the various corrections, are shown in Plate 24. With both viscosity and void ratio changes accounted for, the curvature in the profiles remains; a situation which is incompatible with steady laminar flow in a homogeneous saturated specimen.

Since the specimens were formed by rodding successive layers, it is to be expected that some air might be trapped in the process. On the basis of the consolidation specimen, the degree of saturation of specimens at the time of molding should have been in the order of 96%. This corresponds to 0.0354 $cm.^3$ of air to 1 $cm.^3$ of water. If the air was present as isolated bubbles through out the specimen, the air pressure would be equal to the pressure in the surrounding fluid. By Henry's law[1], the solubility of a gas in a liquid is directly proportional to the pressure. As the neutral pressures decreased during the course of the frost heave tests, according to Henry's law, air should be released from the pore water, provided that it was saturated at the beginning. The maximum negative stress of 642 cm. of water was recorded in Test 13B at 110.2 hours (Table III(E)). The corresponding absolute pressure would be 1033 - 642 = 391 cm. of water. Assuming that the trapped air was at atmospheric pressure (1033 cm. of water, absolute) and that the pore water was air saturated initially, a pressure drop to 391 cm. of water should result in the dissolved air content dropping to 391/1033 or 0.38 of its initial value. At a pressure of one atmosphere and at 20°C., 1 $cm.^3$ of water can retain

[1]See any standard textbook on the Fundamentals of Physical Chemistry.

approximately 0.0187 $cm.^3$ of dissolved air (26). At a pressure of 391 cm. of water, 0.00707 $cm.^3$ could be retained. Thus 0.0116 $cm.^3$ would be released, increasing the undissolved air content to 0.0470 cm. /cm. . However, the effect of temperature variation has yet to be included. Samples were molded at room temperature, which for the present purposes will be assumed to be 20°C. During test temperatures were dropped throughout the system. For the test, time and elevation indicated above, the temperature was approximately 0°C. Between 20 and 0°C. the saturated air capacity of water changes from 0.0187 to 0.0292 $cm.^3/cm.^3$, so that 0.0105 $cm.^3/cm.^3$ could be absorbed, leaving the degree of saturation and the quantity of undissolved air approximately the same as when the sample was molded. Under conditions imposed during test changes, the solubility of air in water would appear to be small when the trapped air is isolated from the atmosphere. Where a specimen becomes unsaturated due to negative pore stresses exceeding the capillarity of the material, the air space in the voids will be vented to the atmosphere. Air absorbed by the water due to temperature decrease will be replaced from the atmosphere and the degree of saturation of the specimen will be unaltered. Hence the solubility factor can be ignored.

When negative stresses in the frost heave specimens exceed the capillarity of the specimen material, it is to be expected that there will be curvature in the total head profiles (See Chapter II). Variations in hydraulic gradient and permeability due to increasing

negative stresses were predicted as indicated on Plate 7. These quantities, computed from experimental data, are listed in Table IX and plotted on Plates 25 and 26. The experimental hydraulic gradient profiles are similar to those predicted on the basis of capillary desaturation. A similar comparison of the permeability profiles indicates that the permeability decreases in the direction of flow as predicted but with reversed curvature. The curvature of the permeability profile is dependent on the hydraulic gradient profile. The permeability times the hydraulic gradient must equal the superficial velocity, which is a constant along the flow path, for steady flow conditions. It can be shown that the curvature of the permeability profile can be reversed by increasing or decreasing the curvature of the hydraulic gradient profile. Thus, the experimental permeability profiles are similar to those predicted. It was shown previously, that the pressures in the pore water increases negatively from zero at the reservoir to a maximum at the frost line. If the capillarity of the material falls within this range of pressures, it would be expected that the test specimen would contain one zone having a constant degree of saturation near 100%, and a second in which the degree of saturation decreases with increasing negative pressure. If water moves through the saturated zone subject to Darcy's law, it should be registered on the permeability and hydraulic gradient profiles as vertical lines, indicating that those quantities are constants within that zone. On this basis, no saturated zone can be identified (Plates 25 and 26).

One capillarity determination was carried out using apparatus similar to Beskow's simplified capillarimeter (6), with the exception that a water over mercury column was used to apply negative stress to the specimen. The capillarity value obtained was 605 cm. of water. This falls within the range of 400 - 1000 cm. given by Beskow for fine silt in the loose state. It seems reasonable, considering that the specimen material was a well graded silt having a D_{10} value in the fine silt range. If the determined value of capillarity is correct, then the only place that desaturation should have occurred is in the vicinity of the top manometer for Test 13B, at 107.8 to 110.2 hours. This indicates that, while the profiles discussed above displayed characteristics that could be explained for negative stresses greater than the capillarity of the material, in fact, stresses were less than the capillarity. For water movement during ice segregation, it appears that the hydrodynamical characteristics of flow are not explained by the theory presented in Chapter II. Further evidence to support this finding is to be found on Plate 27 which shows that the permeability decreased with increasing negative pressures throughout the measured pressure range and that corrections accounting for changes in temperature and void ratio did not alter the situation. Pressure-permeability curves are shown for various times, on Plate 28 which was plotted from the data in Table X. Although the curves tended to shift to the left with time, they retained a similarity of shape.

The most of the shifting took place during the first thirty four hours of the test. Plate 20E shows that this was the period in which the initial drop in the cold room temperature produced relatively rapid increases in the heave, depth of frost line and the piezometric pressure. The thirty four hour pressure-permeability curve appears to be coincident with the subsequent curves. This suggests that apart from effects due to abrupt changes in the applied freezing temperature, the pressure-permeability relationship is defined by a unique curve.

The sensitivity of the permeability to pressure changes increased with decreasing pressure values. Extreme sensitivity was exhibited as the negative pressures approached zero. This appears to dismiss any explanation of the pressure-permeability behavior based on the assumption that the capillarity, as determined, was not a reliable measure of the minimum stress required to induce air entry in the specimen. Some explanation other than that outlined in the theory must be sought.

Flow Under Negative Pressure Conditions

It was noted by Beskow (6) that the movement of water to a frost line was similar to the movement of water to a surface where evaporation was taking place. In either case, water in the liquid phase was removed from the soil by the process and the resulting moisture deficiency induced the subsequent flow.

Plate 29 shows the hydraulic gradient profiles at various times during Test 10. Richards, Gardner and Ogata (27) have

published a similar plot for the case of evaporation following the prolonged irrigation of a field plot. This is shown on Plate 30. The similarity between the hydraulic gradient profiles for the two cases, indicates a corresponding similarity in hydrodynamics involved in each. For example, it follows that piezometric pressure and total head, in the evaporation case, will vary in a similar manner to that determined from the frost heave tests. The data of Richards and Weeks (28) are from tests in which water was drawn from a soil column by applying tension to the pore water at one end, after the soil and moisture had come to equilibrium under a lesser tension. On Plate 31 is a comparison between the data from the frost heave tests and the equivalent values for the case of applied tension. The variation in the pore pressures with position and time are given in (a) and (b). The curve designations in (a) refer to the distance from the point of application of tension while in (b) the designations are the distance above the reservoir water level. The differences in the curves during the early stages of the interval considered, can be explained by the fact that in the applied tension case the specimen was initially in equilibrium, while in the frost heave tests freezing was started before gravity drainage was complete. With this exception the variation of negative stress with position and time appears to be similar in the two cases. The similarity of shape carries through to the "the quantity of moisture removed vs. time" and to the variation in permeability with negative pressure, as shown in (c)-(d) and (e)-(f), respectively. In the frost

heave tests no moisture content data was obtained. At the termination of these tests some of the instrumentation was imbedded in frozen soil precluding immediate sectioning of the specimen for moisture content determinations. Beskow (6) has shown that the moisture content in a freezing soil specimen decreases between the water reservoir and the frost line. If the moisture content decreases with increasing negative stresses, it follows that a stress distribution such as that obtained in the frost heave tests should result in the rate of change of moisture content increasing in the direction of flow. Thus, it is probable that there is similarity in the moisture content-pressure relationships. The qualitative agreement among the data indicate that the hydrodynamics of flow under negative pressures is similar whether the pressures are applied or induced.

It has been shown by Schofield (29) and others, that the water content of a soil is a continuous function of the negative stress in the pore water, with the water content decreasing as the negative stresses increase. The moisture content-tension curves obtained by Penner (15) are of the same type as that shown in Plate 31(g). The moisture content is most sensitive to negative pressures at the low pressure values. This indicates that the moisture content reduction does not necessarily involve the entry of air into the specimen. The same situation applies to the pressure-permeability relationships obtained in the frost heave tests. This suggests that the hydrodynamics of flow under negative pressures is dependent on

the moisture-tension relationships. According to Gardner (30) the permeability is a function of the moisture content or the moisture tension. This is apparently accepted by soil physicists dealing with problems including water evaporation from soils. Due to the similarities noted between frost heave and evaporation test data, theory governing the flow of water to an evaporation surface will be discussed.

"Unsaturated" Flow Theory

Where soil moisture-tension relationships are involved, the term "saturated" is used to describe the moisture content when the soil and water are in equilibrium at atmospheric pressure. Under pressures less than atmospheric the moisture content will be decreased leaving the sample "unsaturated". According to Gardner (30) "The basis of the theory of unsaturated flow is the assumption that the volume flux of water per unit area perpendicular to the direction of flow is directly proportional to the potential gradient." This may be expresses as

$$v = k_u \, i \qquad \text{(V.19)}$$

where k_u is the unsaturated coefficient of permeability which is dependent on moisture content or tension. The terms v and i have the same meaning as in Darcy's law for saturated flow. For one dimensional flow in the z direction

$$v = k_u \, dH/dz \qquad \text{(V.19A)}$$

where dH is the total head loss over a distance dz. The continuity may be derived as follows. Consider one dimensional flow in the

z direction through an element having dimension dz, dy and unity normal to y-z. If the superficial velocity of water entering and leaving the element are v and $v + (\partial v/\partial z)dz$, respectively, then the rate of accumulation or depletion of water in the element should be the difference multiplied by the area normal to the direction of flow. i.e. $(\partial v/\partial z)dz(dy\ 1)$. The volume of the element is 1 dy dz. Let the volume of water in the element be V_w and the moisture content on a volume basis θ (i.e. volume of water divided by the volume of the element). $\theta = V_w/dy\,dz$ and $V_w = \theta\,dy\,dz$. The volume of water in the element is governed by flow to or from it.

$$dV_w/dt = (\partial v/\partial z)dy\,dz. \quad \text{and } d/dt(\theta\,dy\,dz) = \partial v/\partial z(dy\,dz)$$

Hence

$$d\theta/dt = dv/dz \qquad \text{(V.20)}$$

Equation (V.20) expresses the condition of continuity. This can be combined with equation (V.19A) as follows.

$$d\theta/dt = -(d/dz)(k_u\,dH/dz)$$

The total head loss (dH) is equal to the change in negative pressure (dh) minus the difference in elevation (dz).

$$d\theta/dt = -\frac{d}{dz}\left(k_u\left(\frac{dh - dz}{dz}\right)\right) = -\frac{d}{dz}\left(k_u\frac{dh}{dz} - 1\right) \qquad \text{(V.21)}$$

Integrating for the case of steady-state flow where $d\theta/dt = 0$.

$$k_u(dh/dz - 1) = C \qquad \text{(V.22)}$$

The quantity in the brackets is the hydraulic gradient, therefore the constant of integration C will be equal to the superficial velocity v. Rewriting as a function of z and integrating

$$z = \int \frac{dh}{1 + v/k_u} \qquad \text{(V.23)}$$

Equation (V.23) gives an unsolved functional relationship for elevation, negative pressure and unsaturated permeability. Gardner (30) presents an empirical equation which relates unsaturated permeability to negative pressures. The expression is as follows:

$$k_u = a/(h^n + b) \qquad \text{(V.24)}$$

where a, b and n are constants. He indicates that the value of n appears to range between one and four. Gardner (31) has produced solutions for equation (V.23) using equation (V.24) and several values of n. The solutions are as follows:

$$n = 1 \qquad z = \frac{1}{\alpha}\ln(\alpha h + \beta) + K \qquad \text{(V.25)}$$

$$n = 3/2 \qquad z = \frac{2}{\alpha}\left[\frac{1}{6\gamma}\ln\left(\frac{\gamma^2 - \gamma\sqrt{h} + h}{(\gamma + \sqrt{h})^2}\right) + \frac{1}{\gamma\sqrt{3}}\tan^{-1}\left(\frac{2\sqrt{h} - \gamma}{\gamma\sqrt{3}}\right)\right] + K \qquad \text{(V.25A)}$$

where $\gamma^3 = \beta/\alpha$

$$n = 2 \qquad z = \frac{1}{\sqrt{\alpha\beta}}\tan^{-1}\left(\sqrt{\frac{\alpha}{\beta}}\,h\right) + K \qquad \text{(V.25B)}$$

$$n = 3 \qquad z = \frac{1}{\alpha}\left[\frac{1}{6\gamma^2}\ln\left(\frac{(\gamma + h)^2}{(\gamma^2 - \gamma h + h^2)}\right) + \frac{1}{\gamma^2\sqrt{3}}\tan^{-1}\left(\frac{2h - \gamma}{\gamma\sqrt{3}}\right)\right] + K \qquad \text{(V.25C)}$$

where $\gamma^3 = \beta/\alpha$

$$n = 4 \qquad z = \frac{1}{\alpha}\left[\frac{1}{4\rho^3\sqrt{2}}\ln\left(\frac{h^2 + \rho h\sqrt{2} + \rho^2}{h^2 - \rho h\sqrt{2} + \rho^2}\right) + \frac{1}{2\rho^3\sqrt{2}}\tan^{-1}\left(\frac{\rho h\sqrt{2}}{\rho^2 - h^2}\right)\right] + K \qquad \text{(V.25D)}$$

where $\rho 4 = \beta/\alpha$

$\alpha = v/a$ and $\beta = \alpha b + 1$, where a and b are obtained from equation (V.24) and v is the superficial velocity. These equations relate the elevation to the piezometric pressure and the superficial velocity.

Unsaturated Flow Theory Applied to Frost Heave Test Data

It was attempted to determine a curve of the type $k_u = a/(h^n + b)$ which would fit the experimental frost heave test results. Equations were obtained by assuming an n-value then taking k_u and h values corresponding to the coordinates of two points on the experimental curve and solving simultaneously to determine a and b. The derived equations were plotted along with the experimental data so that the closeness of fit could be observed (See Plates 32A and 32B). Solutions were obtained for n-values from one to four because the flow equation, (V23), has been solved for these values of n. The indications are that the best fit curve is obtained for n = 1. For n = 1 there was variation in the curve depending on the experimental points used in the solution. Therefore, the "n = 1" curves are by no means an exact representation of the test data. Due to the fact that the fit seemed to improve as the value of n decreased, n = 0.5 was tried, although no corresponding solution of the flow equation is available. These curves (Plate 33B) fit the data rather well and the difference in curves obtained from two different pairs of points, was less than that obtained using other values of n. This indicates that for the

soil used and the conditions imposed in the present testing program, the n-value required to fit a curve of the type $k_u = a/(h^n + b)$ to the experimental pressure-permeability data is smaller than any considered by Gardner (30). As data was obtained for one material only, it was not determined whether it was the sample material or the test conditions which gave rise to the small n-value required in the fitting curve. The lack of a solution to the flow equation (V.23) for the case $n = 0.5$, precludes the continuation of analysis along this line; the derivation being beyond the scope of this dissertation.

Analysis of the Heave Data

The time and heave data are listed in Tables XIII(A) to XIII(E). From Plates 20A to 20E intervals were selected for which the rate of heave appeared to be approximately constant. The rates of heave were determined from the "Heave vs. Time" curves on Plates 34A to 34E. These values are tabulated along with the corresponding distances from the reservoir to the frost line, in Table XIV. The rate of heave is shown as a function of the length of flow path, on Plate 35. For the first cycle of freezing, the rate of heave appears to decrease linearly as the length of flow path increases. Generally, the effect of refreezing was to increase the rate of heave. This effect was most obvious in test 12-12F. In 12A-12D, inclusive, freezing took place with the cold room temperature at -22°F. so that variations in the rate of heave for these tests can be attributed to effects produced by the freezing process itself. In this respect, the development of structure is probably involved. Tests 12E and 12F showed a further increase

in the rate of heave but freezing took place with higher cold room temperatures which could have provided conditions more favorable for ice segregation.

In a number of cases the rate of heave in a particular test was constant for a range of values of the length of flow path. In tests 12B, 12C, 13A and 13B the rates of heave remained constant while the dropping frost line decreased the length of the flow path by 26 to 42%. This indicates that the relationship among factors influencing moisture movements is such the net effect may remain constant even though there is variation in individual factors.

TABLE II

TAPPING POINT LOCATION DATA

TEST	LENGTH	ELEVATION OF MANOMETER TAPPING POINTS (above base support)					FREE WATER SURFACE ELEVATION (above base support)	ELEVATION OF MANOMETER TAPPING POINTS (above free water surface)					ELEVATION OF MANOMETER TAPPINT POINTS (below original sample surface)				
		Manometer						Manometer					Manometer				
		1	2	3	4	5		1	2	3	4	5	1	2	3	4	5
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
9	62.1		22.9	13.0	26.9	18.0	0.3		22.6	12.7	26.6	17.7		39.2	49.0	35.2	44.1
10	62.7	33.5	18.3	13.7	27.7	22.9	0.4	33.1	17.9	13.3	27.3	22.5	29.2	44.6	49.0	35.0	39.8
11	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"
12-12F	23.7	5.8	8.3	10.7	13.2	15.7	3.2	2.6	5.1	7.5	10.0	12.5	17.9	15.4	13.0	10.5	8.0
13-13C	41.5	"	"	"	"	"	"	"	"	"	"	"	35.7	33.2	30.8	28.3	25.8

NOTE: All values listed in the above table are expressed in centimeters.

TABLE III (A)

TOTAL HEAD AND EFFECTIVE PRESSURE DETERMINATIONS
FOR TEST NO. 9

TIME hr.	PIEZOMETRIC PRESSURE cm. of water					TOTAL HEAD cm. of water					EFFECTIVE PRESSURE cm. of water				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
	1	4	2	5	3	1	4	2	5	3	1	4	2	5	3
5.0	*	+4	-4	+4	-4		+31	+19	+22	+9		+82	+99	+102	+120
7.0		-1	-8	-3	-6		+26	+15	+15	+7		+87	+103	+109	+122
8.5		-5	-10	-4	-8		+22	+13	+14	+5		+91	+105	+110	+124
18.3		-15	-18	-9	-11		+12	+5	+9	+2		+101	+113	+115	+127
19.3		-16	-19	-9	-13		+11	+4	+9	0		+102	+114	+115	+129
20.3		-16	-19	-9	-14		+11	+4	+9	-1		+102	+114	+115	+130
21.6		-18	-19	-10	-14		+9	+4	+8	-1		+104	+114	+116	+130
23.5		-21	-23	-13	-14		+6	0	+5	-1		+107	+118	+119	+130
24.6		-18	-20	-13	-14		+9	+3	+5	-1		+104	+115	+119	+130
25.6		-16	-20	-11	-13		+11	+3	+7	0		+102	+115	+117	+129
26.6		-16	-20	-11	-13		+11	+3	+7	0		+102	+115	+117	+129
31.7		-16	-20	-11	-13		+11	+3	+7	0		+102	+115	+117	+129
44.8		-18	-21	-14	-14		+9	+2	+4	-1		+104	+116	+120	+130
47.2		-18	-20	-14	-14		+9	+3	+4	-1		+104	+115	+120	+130
69.5		-34	-26	-15	-14		-7	-3	+3	-1		+120	+121	+121	+130
76.2		-54	-44	-19	-14		-27	-21	-1	-1		+140	+139	+125	+130
90.5		-96	-84	-26	-15		-69	-61	-8	-2		+182	+179	+132	+131
92.3		-100	-89	-29	-16		-73	-66	-11	-3		+186	+184	+135	+132
93.6		-106	-95	-30	-16		-79	-72	-12	-3		+192	+190	+136	+132
96.2		-111	-101	-34	-16		-84	-78	-16	-3		+197	+196	+140	+132
98.2		-113	-105	-36	-16		-86	-82	-18	-3		+199	+200	+142	+132
102.8		-110	-106	-42	-19		-83	-83	-24	-6		+196	+201	+148	+135
114.5		-59	-61	-40	-29		-32	-38	-22	-16		+145	+156	+146	+145
117.1		-52	-52	-39	-29		-25	-29	-21	-16		+138	+147	+145	+145

TABLE III(A) (continued)

TIME hr.	PIEZOMETRIC PRESSURE cm. of water					TOTAL HEAD cm. of water					EFFECTIVE PRESSURE cm. of water				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
	1	4	2	5	3	1	4	2	5	3	1	4	2	5	3
120.0	*	-45	-34	-38	-28		-18	-11	-20	-15		+131	+129	+144	+144
122.2		-48	-34	-40	-31		-21	-11	-22	-18		+134	+129	+146	+147
123.4		-44	-31	-36	-28		-17	-8	-18	-15		+130	+126	+142	+144
125.0		-45	-31	-36	-28		-18	-8	-18	-15		+131	+126	+142	+144
126.2		-49	-48	-39	-29		-22	-25	-21	-16		+135	+143	+145	+145
127.2		-56	-53	-40	-32		-29	-30	-22	-19		+142	+148	+148	+148
128.0		-60	-55	-40	-32		-33	-32	-22	-19		+146	+150	+148	+148
138.3		-89	-83	-49	-38		-62	-60	-31	-25		+175	+178	+154	+154
139.3		-92	-84	-50	-39		-65	-61	-32	-26		+178	+179	+155	+155
140.3		-94	-87	-51	-39		-67	-64	-33	-26		+180	+182	+155	+155
141.3		-97	-89	-53	-40		-70	-66	-35	-27		+183	+184	+156	+156
143.0		-99	-92	-54	-41		-72	-69	-36	-28		+185	+187	+157	+157
145.0		-98	-92	-54	-41		-71	-69	-36	-28		+184	+187	+157	+157
146.5		-101	-94	-58	-43		-74	-71	-40	-30		+187	+189	+159	+159
147.6		-104	-98	-58	-44		-77	-75	-40	-31		+190	+193	+160	+160
149.1		-108	-101	-59	-45		-81	-78	-41	-32		+194	+196	+161	+161
150.0		-116	-110	-64	-49		-89	-87	-46	-36		+202	+205	+165	+165
151.0		-116	-108	-62	-48		-89	-85	-44	-35		+202	+203	+164	+164
152.0		-118	-110	-63	-48		-91	-87	-45	-35		+204	+205	+164	+164
152.8		-127	-115	-65	-49		-100	-92	-47	-36		+213	+210	+165	+165
162.3		-157	-147	-68	-58		-130	-124	-60	-45		+243	+242	+174	+174
163.8		-164	-152	-82	-60		-137	-129	-64	-47		+250	+247	+176	+176
165.0		-166	-156	-83	-61		-139	-133	-65	-48		+252	+251	+177	+177
320.0		-6	-10	-10	-13		+21	+13	+8	0		+90	+105	+126	+129
330.3		-74	-61	-27	-19		-47	-38	-9	-6		+160	+156	+133	+135
331.1		-82	-68	-31	-21		-55	-45	-13	-8		+168	+163	+137	+137

TABLE III(A) (continued)

TIME hr.	PIEZOMETRIC PRESSURE cm. of water					TOTAL HEAD cm. of water					EFFECTIVE PRESSURE cm. of water				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
	1	4	2	5	3	1	4	2	5	3	1	4	2	5	3
332.0	*	-98	-83	-42	-28	*	-71	-60	-24	-15		+184	+178	+148	+144
333.0		-107	-90	-44	-27		-80	-67	-26	-14		+193	+185	+150	+143
335.1		-121	-114	-47	-28		-94	-91	-29	-15		+207	+209	+153	+144
336.2		-128	-110	-53	-32		-101	-87	-35	-19		+214	+205	+159	+148
337.1		-134	-114	-56	-35		-107	-91	-38	-22		+220	+209	+162	+151
338.2		-147	-127	-64	-39		-120	-104	-46	-26		+233	+222	+170	+155
339.0		-144	-126	-61	-36		-117	-103	-43	-23		+230	+221	+167	+152
340.1		-145	-127	-62	-40		-118	-104	-44	-27		+231	+222	+168	+156
341.5		-151	-134	-68	-45		-124	-111	-50	-32		+237	+229	+174	+161
342.5		-155	-137	-70	-47		-128	-114	-52	-34		+241	+232	+176	+163
344.2		-163	-144	-76	-52		-136	-121	-58	-39		+249	+239	+182	+168
345.2		-165	-146	-77	-54		-138	-123	-59	-41		+251	+241	+183	+170
347.8		-177	-155	-85	-61		-150	-132	-67	-48		+263	+250	+191	+177
354.3		-206	-177	-98	-79		-179	-154	-80	-66		+292	+272	+204	+195
357.3		-220	-193	-107	-79		-193	-170	-89	-66		+306	+288	+213	+195
360.9		-226	-198	-111	-82		-199	-175	-93	-69		+312	+293	+217	+198
362.6		-231	-204	-119	-87		-204	-181	-101	-74		+317	+299	+225	+203
364.1		-220	-197	-114	-84		-193	-174	-96	-71		+306	+292	+220	+200
366.0		-212	-190	-111	-84		-185	-167	-93	-71		+298	+285	+217	+200
367.0		-211	-189	-111	-84		-184	-166	-93	-71		+297	+284	+217	+200
378.8		-234	-211	-124	-95		-207	-188	-106	-82		+320	+306	+230	+211
380.3		-236	-213	-126	-96		-209	-190	-108	-83		+322	+308	+232	+212
381.2		-239	-214	-128	-97		-212	-191	-110	-84		+325	+309	+234	+213
382.6		-240	-215	-129	-97		-213	-192	-111	-84		+326	+310	+235	+213
384.5		-242	-218	-130	-99		-215	-195	-112	-86		+328	+313	+236	+215
386.0		-244	-221	-132	-100		-217	-198	-114	-87		+330	+316	+238	+216
387.2		-235	-213	-129	-99		-208	-190	-111	-86		+321	+308	+235	+215

TABLE III(A) (continued)

TIME hr.	PIEZOMETRIC PRESSURE cm. of water					TOTAL HEAD cm. of water					EFFECTIVE PRESSURE cm. of water				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
	1	4	2	5	3	1	4	2	5	3	1	4	2	5	3
388.8	*	-242	-216	-131	-100		-215	-196	-113	-87		+328	+311	+237	+216
390.8	-	-249	-222	-134	-101		-222	-199	-116	-88		+335	+317	+240	+217
392.4		-257	-228	-136	-103		-230	-205	-118	-90		+343	+323	+242	+219
403.0		-276	-249	-148	-113		-249	-226	-130	-100		+362	+344	+254	+229
404.0		-276	-250	-150	-113		-249	-227	-132	-100		+362	+345	+256	+229
406.0		-289	-256	-157	-119		-262	-233	-139	-106		+375	+351	+263	+235
408.3		-280	-249	-150	-117		-253	-226	-132	-104		+366	+344	+256	+233
410.3		-279	-249	-151	-118		-252	-226	-133	-105		+365	+344	+257	+234
412.0		-279	-249	-148	-120		-252	-226	-130	-107		+365	+344	+254	+236
413.1		-234	-249	-148	-121		-207	-226	-130	-108		+320	+344	+254	+237
415.0		-219	-247	-128	-123		-192	-224	-110	-110		+305	+342	+234	+239
416.0		-203	-244	-117	-123		-176	-221	-99	-110		+289	+339	+223	+239
426.3		-284	-275	-106	-140		-257	-252	-88	-127		+370	+370	+212	+256
428.7		-298	-286	-106	-146		-271	-263	-88	-133		+384	+381	+212	+262
430.0		-298	-284	-106	-144		-271	-261	-88	-131		+384	+379	+212	+260
432.3		-302	-288	-105	-152		-275	-265	-87	-139		+388	+383	+211	+268
434.3		-296	-277	-104	-151		-269	-254	-86	-138		+382	+372	+210	+267
436.0		-286	-266	-102	-151		-259	-243	-84	-138		+372	+361	+208	+267
438.0		-274	-254	-101	-158		-247	-231	-83	-145		+360	+349	+207	+274
450.3		-302	-295	-86	-189		-275	-272	-68	-176		+388	+390	+192	+305
452.2		-306	-305	-86	-194		-279	-282	-68	-181		+392	+400	+192	+310
454.3		-314	-312	-83	-157		-287	-289	-65	-144		+400	+407	+189	+273
455.8		-320	-314	-82	-96		-293	-291	-64	-83		+406	+409	+188	+212

* Manometer 1 was inoperative during this test.

TABLE III(B)

TOTAL HEAD AND EFFECTIVE PRESSURE DETERMINATIONS
FOR TEST NO. 10

TIME hr.	PIEZOMETRIC PRESSURE cm. of water					TOTAL HEAD cm. of water					EFFECTIVE PRESSURE cm. of water				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
	1	4	5	2	3	1	4	5	2	3	1	4	5	2	3
6.0	-1	0	+9	+13	+15	+32	+27	+32	+31	+28	+74	+85	+85	+94	+101
16.5	-9	-8	-4	-1	+1	+24	+19	+19	+17	+14	+82	+93	+100	+108	+115
19.0	-10	-10	-6	-4	-5	+23	+17	+17	+14	+8	+83	+95	+102	+111	+121
21.6	-10	-10	-8	-4	-6	+23	+17	+15	+14	+7	+83	+95	+104	+111	+122
24.0	-10	-10	-8	-5	-9	+23	+17	+15	+13	+4	+83	+95	+104	+112	+125
26.4	-10	-10	-8	-5	-8	+23	+17	+15	+13	+5	+83	+95	+104	+112	+124
30.0	-14	-14	-11	-9	-9	+19	+13	+12	+9	+4	+87	+99	+107	+116	+125
40.4	-14	-15	-13	-10	-9	+19	+12	+10	+8	+4	+87	+100	+109	+117	+125
42.5	-32	-43	-23		-21	+1	-16	0		-8	+105	+128	+119		+137
46.0	-18	-15	-9	-8	-8	+13	+12	+14	+10	+5	+91	+100	+105	+115	+124
50.5	-34	-20	-15	-11	-9	-1	+7	+8	+7	+4	+107	+105	+111	+118	+127
54.7	-43	-20	-15	-11	-9	-10	+7	+8	+7	+4	+116	+105	+111	+118	+127
67.3	-60	-23	-16	-10	-9	-27	+4	+7	+8	+4	+133	+108	+112	+117	+127
71.0	-60	-23	-16	-9	-9	-27	+4	+7	+9	+4	+133	+108	+112	+116	+127
74.9	-60	-23	-15	-9	-8	-27	+4	+8	+9	+5	+133	+108	+111	+116	+126
78.9	-58	-26	-14	-9	-8	-25	+1	+9	+9	+5	+131	+111	+110	+116	+126
88.5	-43	-14	-4	-3	+3	-10	+12	+19	+15	+16	+116	+100	+100	+110	+113
90.5	-43	-18	-8	0	0	-10	+9	+15	+18	+13	+116	+103	+104	+107	+116
93.5	-52	-24	-13	-4	-4	-19	+3	+10	+14	+9	+125	+109	+109	+111	+120
95.5	-63	-32	-19	-10	-8	-30	-5	+4	+8	+5	+136	+117	+115	+117	+124
97.4	-66	-28	-14	-6	-3	-33	-1	+9	+12	+10	+139	+113	+110	+113	+119
99.6	-71	-29	-15	-8	-4	-38	-2	+8	+10	+9	+144	+114	+111	+115	+120
101.7	-76	-32	-16	-9	-6	-43	-5	+7	+9	+7	+149	+117	+112	+116	+122

TABLE III(B) (continued)

TIME hr.	PIEZOMETRIC PRESSURE cm. of water					TOTAL HEAD cm. of water					EFFECTIVE PRESSURE cm. of water				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
	1	4	5	2	3	1	4	5	2	3	1	4	5	2	3
112.6	-93	-44	-21	-13	-8	-60	-17	+2	+5	+5	+166	+129	+117	+120	+124
113.7	-97	-48	-25	-15	-9	-64	-21	-2	+3	+4	+170	+133	+121	+122	+125
115.6	-96	-47	-24	-13	-8	-63	-20	-1	+5	+5	+169	+132	+120	+120	+124
117.5	-97	-49	-24	-14	-8	-64	-22	-1	+4	+5	+170	+134	+120	+121	+124
119.4	-103	-55	-29	-18	-10	-70	-28	-6	0	+3	+180	+140	+125	+125	+126
121.4	-101	-54	-29	-16	-6	-68	-27	-6	+2	+7	+174	+139	+125	+123	+122
126.2	-100	-54	-29	-15	-8	-67	-27	-6	+3	+5	+173	+139	+125	+122	+124
136.4	-96	-57	-33	-19	-11	-63	-30	-10	-1	+2	+169	+142	+129	+126	+127
138.4	-95	-50	-34	-20	-11	-62	-23	-11	-2	+2	+168	+135	+130	+127	+127
141.3	-100	-55	-34	-20	-11	-67	-28	-11	-2	+2	+173	+140	+130	+127	+127
143.4	-131	-64	-38	-21	-13	-98	-37	-15	-3	0	+204	+149	+134	+128	+129
145.6	-157	-69	-39	-23	-13	-124	-42	-16	-5	0	+230	+154	+135	+130	+129
148.9	-188	-79	-40	-23	-14	-155	-50	-17	-5	-1	+261	+164	+136	+130	+130
153.5	-227	-103	-52	-26	-16	-194	-76	-29	-8	-3	+300	+188	+148	+133	+132
156.0	-258	-118	-60	-29	-18	-225	-91	-37	-11	-5	+331	+203	+156	+136	+134
158.0	-282	-135	-67	-33	-19	-249	-108	-44	-15	-6	+355	+220	+163	+140	+135
160.5	-300	-150	-77	-37	-20	-267	-123	-54	-19	-7	+373	+235	+173	+144	+136
163.0	-323	-170	-92	-48	-26	-290	-143	-69	-30	-13	+396	+255	+188	+155	+142
165.5	-334	-180	-98	-50	-26	-301	-153	-75	-32	-13	+407	+265	+194	+157	+142
167.9	-340	-186	-105	-53	-26	-307	-159	-82	-35	-13	+413	+271	+201	+160	+142
169.2	-341	-190	-110	-55	-28	-308	-163	-87	-37	-15	+414	+275	+206	+162	+144
171.7	-341	-202	-121	-64	-35	-308	-175	-98	-46	-22	+414	+287	+217	+171	+151
173.4	-343	-205	-126	-69	-37	-310	-178	-103	-51	-24	+416	+290	+222	+176	+153
174.3	-343	-208	-130	-71	-39	-310	-181	-107	-53	-26	+416	+293	+226	+178	+155
178.1	-310	-219	-139	-82	-45	-277	-192	-116	-64	-32	+383	+304	+235	+189	+161

TABLE III(C)

TOTAL HEAD AND EFFECTIVE PRESSURE DETERMINATIONS
FOR TEST NO. 11

TIME hr.	PIEZOMETRIC PRESSURE cm. of water					TOTAL HEAD cm.of water					EFFECTIVE PRESSURE cm. of water				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
	1	4	5	2	3	1	4	5	2	3	1	4	5	2	3
7.0	-1	-6	-8	-4	+1	+32	+21	+10	+19	+9	+74	+91	+104	+111	+115
11.0	-4	0	-3	-3	0	+29	+27	+15	+20	+10	+77	+85	+ 99	+110	+116
14.6	-5	-4	-5	-4	0	+28	+23	+13	+19	+9	+78	+89	+101	+111	+116
22.7	-9	-5	-5	-4	0	+24	+22	+13	+19	+9	+82	+90	+101	+111	+116
27.7	-13	-11	-9	-3	0	+20	+16	+9	+20	+10	+86	+96	+105	+110	+116
29.8	-10	-6	-6	-3	0	+23	+21	+12	+20	+10	+83	+91	+102	+110	+116
33.8	-13	-10	-8	-5	-1	+20	+17	+10	+18	+8	+86	+95	+104	+112	+117
46.8	-15	-11	-9	-6	-1	+18	+16	+9	+17	+7	+88	+96	+105	+113	+117
49.7	-18	-18	-14	-9	-3	+15	+9	+4	+14	+4	+91	+103	+110	+116	+119
53.3	-18	-18	-12	-9	-3	+15	+9	+6	+14	+4	+91	+103	+108	+116	+119
56.7	-18	-11	-9	-8	-3	+15	+16	+9	+15	+5	+91	+96	+105	+115	+119
60.6	-18	-11	-9	-6	-3	+15	+16	+9	+17	+7	+91	+96	+105	+113	+119
71.0	-21	-14	-9	-6	0	+12	+13	+9	+17	+7	+94	+99	+105	+113	+116
75.8	-26	-19	-13	-8	+1	+7	+8	+5	+15	+5	+99	+104	+109	+115	+115
80.6	-26	-15	-8	-5	+1	+7	+12	+10	+18	+8	+99	+100	+104	+112	+115
84.0	-28	-15	-10	-6	+1	+5	+12	+8	+17	+7	+101	+100	+106	+113	+116
94.7	-35	-23	-14	-9	-3	-2	+4	+4	+14	+4	+108	+108	+110	+116	+119
99.8	-39	-26	-15	-10	-4	-6	+1	+3	+13	+3	+112	+111	+111	+117	+120
102.7	-59	-101	-01	-39	-25	-26	-74	-63	-16	-26	+132	+186	+177	+146	+141
170.0	-6	+18		+6	+5	+27	+45		+29	+18	+79	+67		+101	+111
175.3	-9	-8	-8	0	+1	+24	+19	+10	+23	+14	+82	+93	+104	+107	+115
181.1	-9	-4	-5	-1	0	+24	+23	+13	+22	+13	+82	+89	+101	+106	+116
191.1	-11	-5	-6	-1	-1	+22	+22	+12	+22	+12	+84	+90	+102	+106	+117

TABLE III(C) (continued)

TIME hr. (1)	PIEZOMETRIC PRESSURE cm. of water (2)	(3)	(4)	(5)	(6)	TOTAL HEAD cm. of water (7)	(8)	(9)	(10)	(11)	EFFECTIVE PRESSURE cm. of water (12)	(13)	(14)	(15)	(16)
	1	4	5	2	3	1	4	5	2	3	1	4	5	2	3
195.9	-14	-9	-8	-4	0	+19	+18	+15	+14	+13	+ 87	+94	+104	+111	+116
201.6	-16	-10	-9	-5	-1	+17	+17	+14	+13	+12	+89	+95	+105	+112	+117
214.8	-21	-13	-9	-5	-1	+12	+14	+14	+13	+12	+94	+98	+105	+112	+117
219.7	-25	-16	-11	-6	-1	+8	+11	+12	+12	+12	+98	+101	+107	+113	+117
223.7	-26	-18	-10	-8	0	+7	+9	+13	+10	+13	+99	+103	+106	+115	+116
227.1	-30	-18	-13	-8	-4	+3	+9	+10	+10	+9	+103	+103	+109	+115	+120
238.5	-42	-26	-16	-10	-6	-9	+1	+7	+8	+7	+115	+111	+112	+117	+122
244.8	-50	-43	-30	-20	-13	-17	-17	-7	-2	0	+123	+128	+126	+127	+129
250.4	-35	-23	-20	-10	-4	-2	+4	+3	+8	+9	+108	+108	+116	+117	+120
262.7	-49	-31	-20	-13	-6	-16	-4	+3	+5	+7	+122	+116	+116	+120	+122
265.8	-53	-39	-23	-16	-8	-20	-12	0	+2	+5	+126	+124	+119	+123	+124
270.7	-55	-37	-21	-13	-8	-22	-10	+2	+5	+5	+128	+122	+117	+120	+124
275.0	-59	-42	-25	-16	-10	-26	-15	-2	+2	+3	+132	+127	+121	+123	+126
287.5	-69	-47	-25	-18	-10	-36	-20	-2	0	+3	+142	+132	+121	+125	+126
292.0	-73	-52	-29	-19	-11	-40	-25	-6	-1	+2	+146	+137	+125	+126	+127
297.6	-77	-53	-30	-19	-11	-44	-26	-7	-1	+2	+150	+138	+126	+126	+127
301.3	-81	-57	-33	-20	-13	-48	-30	-10	-2	0	+154	+142	+129	+127	+129
310.5	-87	-62	-35	-23	-15	-54	-35	-12	-5	-2	+160	+147	+131	+130	+131
316.1	-86	-62	-35	-23	-14	-53	-35	-12	-5	-1	+159	+147	+131	+130	+130
334.7	-91	-62	-36	-23	-14	-58	-35	-13	-5	-1	+164	+147	+132	+130	+130
340.8	-102	-72	-48	-30	-20	-69	-45	-25	-12	-7	+175	+157	+144	+137	+136
345.5	-101	-67	-38	-23	-15	-68	-40	-15	-5	-2	+174	+151	+134	+130	+129
349.5	-106	-72	-42	-25	-18	-73	-45	-19	-7	-5	+179	+157	+138	+132	+132
358.9	-116	-79	-45	-26	-19	-83	-52	-22	-8	-6	+189	+164	+141	+133	+133
364.8	-126	-98	-59	-39	-24	-93	-71	-36	-21	-11	+199	+183	+155	+146	+140
369.6	-127	-86	-48	-29	-19	-94	-59	-25	-11	-6	+200	+171	+144	+136	+135
382.7	-139	-97	-57	-31	-23	-106	-70	-34	-13	-10	+212	+182	+153	+138	+139

TABLE III(C) (continued)

TIME hr.	PIEZOMETRIC PRESSURE cm. of water					TOTAL HEAD cm. of water					EFFECTIVE PRESSURE cm. of water				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
	1	4	5	2	3	1	4	5	2	3	1	4	5	2	3
390.7	-141	-106	-64	-38	-26	-108	-79	-41	-15	-13	+214	+191	+160	+145	+142
397.0	-118	-86	-50	-31	-23	-85	-59	-27	-8	-10	+191	+171	+146	+138	+139
406.6	-150	-103	-62	-34	-26	-117	-76	-39	-11	-13	+223	+188	+158	+141	+142
417.3	-105	-79	-47	-24	-21	-72	-52	-24	-1	-8	+178	+164	+143	+131	+137
430.5	-161	-105	-49	-25	-26	-128	-78	-26	-2	-13	+234	+190	+145	+132	+142
437.0	-171	-120	-63	-34	-29	-138	-93	-40	-11	-16	+244	+205	+159	+141	+145
445.8	-185	-127	-71	-24	-29	-152	-100	-48	-2	-16	+258	+212	+167	+131	+145
455.0	-223	-146	-82	-4	-29	-190	-119	-59	+19	-16	+296	+231	+178	+111	+145
462.3	-221	-159	-90	-25	-24	-188	-132	-67	-2	-11	+294	+244	+186	+132	+140
583.0	-13	-11	-8	-4	+1	+20	+16	+15	+19	+14	+86	+96	+104	+111	+115
598.5	-20	-13	-9	-5	-1	+13	+14	+14	+18	+12	+93	+98	+105	+112	+117
612.5	-35	-19	-11	-8	-3	-2	+8	+12	+15	+10	+108	+104	+107	+115	+119
623.7	-54	-31	-20	-11	-6	-21	-4	+3	+12	+7	+127	+116	+116	+118	+122
633.2	-69	-44	-26	-16	-9	-36	-17	-3	+7	+4	+142	+129	+122	+123	+125
649.7	-96	-68	-43	-28	-19	-63	-41	-20	-5	-6	+169	+153	+139	+135	+135
670.5	-86	-62	-42	-29	-20	-53	-35	-19	-6	-7	+159	+147	+138	+136	+136
680.5	-84	-58	-40	-28	-18	-51	-31	-17	-5	-5	+157	+143	+136	+155	+134
694.7	-109	-76	-49	-33	-23	-76	-49	-26	-10	-10	+182	+161	+145	+140	+139
700.0	-117	-90	-61	-42	-29	-84	-63	-38	-19	-16	+190	+175	+157	+149	+145
718.7	-88	-64	-45	-31	-20	-55	-37	-22	-8	-7	+161	+149	+141	+138	+136
729.2	-115	-77	-54	-36	-26	-82	-50	-31	-13	-13	+188	+162	+150	+143	+142
742.8	-117	-83	-55	-38	-26	-84	-56	-32	-15	-13	+190	+168	+151	+145	+142
752.6	-113	-86	-57	-34	-25	-80	-59	-34	-11	-12	+186	+171	+153	+141	+141
769.4	-133	-95	-64	-34	-29	-100	-68	-41	-11	-16	+206	+180	+160	+141	+145
779.4	-146	-106	-69	-26	-28	-113	-79	-46	-3	-15	+219	+201	+165	+133	+144
790.5	-132	-98	-66	-19	-25	-99	-71	-43	+4	-12	+205	+183	+162	+126	+141

TABLE (continued)
III(C)

TIME hr.	PIEZOMETRIC PRESSURE cm. of water					TOTAL HEAD cm. of water					EFFECTIVE PRESSURE cm. of water				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
	1	4	5	2	3	1	4	5	2	3	1	4	5	2	3
891.2	-35	-29	-21	-4	-1	-2	-2	-2	+14	+12	+108	+114	+117	+111	+117
900.7	-33	-21	-15	-1	+3	0	+6	+8	+17	+16	+106	+106	+111	+108	+113
910.6	-37	-25	-18	-1	+1	-4	+2	+5	+17	+14	+110	+110	+114	+108	+115
916.3	-42	-29	-19	-4	+3	-9	-2	+4	+14	+16	+115	+114	+115	+111	+113
921.3	-45	-32	-21	-5	0	-12	-5	+2	+13	+13	+118	+117	+117	+112	+116
934.7	-78	-50	-34	-10	-4	-45	-23	-11	+8	+9	+151	+135	+130	+117	+120
939.9	-98	-65	-43	-14	-6	-65	-38	-20	+4	+7	+171	+150	+139	+121	+122
945.8	-107	-77	-50	-18	-10	-74	-50	-27	0	+3	+180	+162	+146	+125	+126
958.4	-129	-91	-60	-21	-14	-96	-63	-37	-3	-1	+202	+176	+156	+128	+130
963.1	-135	-99	-65	-3*	0*	-102	-72	-42	+15	+13	+208	+184	+161	+110	+116
972.2	-124	-93	-63			-91	-66	-40			+197	+178	+159		
982.6	-136	-98	-67			-103	-71	-44			+209	+183	+163		
987.2	-140	-103	-71			-107	-76	-48			+213	+188	+167		
996.8	-150	-111	-76			-117	-84	-53			+223	+196	+172		
1006.6	-165	-121	-82			-132	-94	-59			+238	+206	+178		
1011.1	-160	-120	-81			-127	-93	-58			+233	+205	+177		
1014.9	-157	-117	-79			-122	-90	-56			+230	+203	+175		
1020.4	-163	-121	-82			-130	-94	-59			+236	+206	+178		
1030.6	-178	-130	-88			-145	-103	-65			+251	+215	+184		
1035.3	-181	-134	-91			-148	-107	-68			+254	+219	+187		
1043.6	-185	-138	-93			-152	-111	-70			+258	+223	+189		
1054.6	-239	-170	-116			-206	-143	-93			+312	+255	+212		
1066.0	-236	-179	-121			-203	-152	-98			+309	+264	+217		
1078.7	-252	-186	-127			-219	-159	-104			+325	+271	+223		
1091.3	-199	-155	-103			-166	-128	-80			+272	+240	+199		
1127.1	-200	-141	-97			-167	-114	-74			+273	+226	+193		
1155.4	-254	-186	-128			-221	-159	-105			+327	+271	+224		

* Manometers 2 and 3 failed at 963 hours.

TABLE III(D)

TOTAL HEAD AND EFFECTIVE PRESSURE DETERMINATIONS
FOR ALL OF TEST NO. 12

TIME hr.	PIEZOMETRIC PRESSURE cm. of water					TOTAL HEAD cm. of water					EFFECTIVE PRESSURE cm. of water				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
	5	4	3	2	1	5	4	3	2	1	5	4	3	2	1
	Test No. 12														
2.2	-6	-5	-5	-3	-9	+7	+5	+3	+2	-6	+30	+36	+42	+45	+57
5.0	-6	-5	-5	-3	-11	+7	+5	+3	+2	-8	+30	+36	+42	+45	+59
17.4	-8	-8	-8	-5	-14	+6	+2	0	0	-11	+32	+39	+45	+47	+62
19.4	-8	-8	-8	-5	-14	+6	+2	0	0	-11	+32	+39	+45	+47	+62
22.9	-8	-8	-8	-5	-14	+6	+2	0	0	-11	+32	+39	+45	+47	+62
25.3	-8	-8	-8	-5	-14	+6	+2	0	0	-11	+32	+39	+45	+47	+62
29.3	-8	-8	-6	-5	-15	+6	+2	+2	0	-12	+32	+39	+43	+47	+63
41.5	-19	-10	-11	-6	-14	-6	0	-3	-1	-11	+45	+41	+48	+48	+62
42.8	-24	-11	-11	-6	-6	-11	-1	-3	-1	-3	+50	+42	+48	+48	+54
44.5	-31	-13	-13	-6	-4	-18	-3	-5	-1	-1	+57	+44	+50	+48	+52
46.1	-24	-13	-11	-6	-4	-11	-3	-3	-1	-1	+50	+44	+48	+48	+52
47.5	-19	-11	-11	-6	-4	-6	-1	-3	-1	-1	+45	+42	+48	+48	+52
49.0	-15	-10	-9	-5	-4	-2	0	-1	0	-1	+41	+41	+46	+47	+52
55.0	-11	-8	-9	-6	-5	+2	+2	-1	-1	-2	+37	+39	+46	+48	+53
65.5	-10	-8	-9	-6	-5	+3	+2	-1	-1	-2	+36	+39	+46	+48	+53
67.3	-10	-8	-9	-5	-5	+3	+2	-1	0	-2	+36	+39	+46	+47	+53
70.0	-10	-8	-9	-5	-4	+3	+2	-1	0	-1	+36	+39	+46	+47	+52
72.0	-15	-13	-11	-5	-4	-2	-3	-3	0	-1	+41	+44	+48	+47	+52
74.0	-14	-9	-10	-5	-4	-1	+1	-2	0	-1	+40	+40	+47	+47	+52
77.3	-16	-11	-10	-5	-4	-3	-1	-2	0	-1	+42	+42	+47	+47	+52
79.1	-21	-13	-11	-5	-4	-8	-3	-3	0	-1	+47	+44	+48	+47	+52
89.5	-64	-21	-19	-6	-4	-53	-11	-11	-1	-1	+90	+52	+56	+48	+52
90.0	-73	-26	-23	-6	-5	-60	-16	-15	-1	-2	+99	+57	+60	+48	+53
91.3	-58	-23	-20	-6	-4	-45	-13	-12	-1	-1	+84	+54	+57	+48	+52

TABLE III (D) (continued)

TIME hr. (1)	PIEZOMETRIC PRESSURE cm. of water (2)	(3)	(4)	(5)	(6)	(7)	(8)	TOTAL HEAD cm. of water (9)	(10)	(11)	(12)	EFFECTIVE PRESSURE cm. of water (13)	(14)	(15)	(16)
	5	4	3	2	1	5	4	3	2	1	5	4	3	2	1
92.5	-44	-19	-18	-6	-4	-31	-9	-10	-1	-1	+70	+50	+45	+48	+52
94.1	-36	-16	-16	-6	-4	-23	-6	-8	-1	-1	+62	+47	+53	+48	+52
95.1	-77	-28	-23	-6	-5	-64	-18	-15	-1	-2	+103	+59	+60	+48	+53
96.0	-83	-29	-24	-6	-5	-70	-19	-16	-1	-2	+109	+60	+61	+48	+53
99.2	-110	-36	-28	-6	-5	-97	-26	-20	-1	-2	+136	+67	+65	+48	+53
100.2	-120	-43	-29	-6	-5	-107	-33	-21	-1	-2	+146	+74	+66	+48	+53
113.5	-185	-67	-36	-8	-5	-172	-57	-28	-3	-2	+211	+98	+73	+50	+53
114.5	-190	-67	-38	-8	-5	-177	-57	-30	-3	-2	+216	+98	+75	+50	+53
115.5	-194	-68	-38	-8	-5	-181	-58	-30	-3	-2	+220	+99	+75	+50	+53

Test No. 12A

2.1	-10	-5	-8	-4	-4	+3	+5	0	+1	-1	+36	+36	+45	+46	+52
4.2	-10	-4	-8	-4	-3	+ 3	+6	0	+1	0	+36	+35	+45	+46	+51
5.5	-10	-3	-8	-4	-3	+3	+7	0	+1	0	+36	+34	+45	+46	+51
7.5	-31	-15	-11	-5	-3	-18	-5	-3	0	0	+57	+46	+48	+47	+51
8.5	-42	-10	-8	-4	-3	-29	0	0	+1	0	+68	+41	+45	+46	+51
10.2	-84	-24	-14	-6	-4	-71	-14	-6	-1	-1	+110	+55	+51	+48	+52
11.3	-142	-39	-21	-8	-4	-129	-29	-13	-3	-1	+168	+70	+59	+50	+52
11.8	-178	-54	-30	-9	-4	-165	-44	-22	-4	-1	+204	+85	+67	+51	+52
14.4	-286	-106	-69	-13	-4	-273	-96	-61	-8	-1	+212	+137	+106	+55	+52
15.0	-294	-115	-73	-13	-5	-281	-105	-65	-8	-2	+220	+146	+110	+55	+53
23.4	-352	-140	-96	-14	-10	-339	-130	-88	-9	-7	+378	+171	+133	+56	+58

TABLE III(D) (continued)

TIME hr.	PIEZOMETRIC PRESSURE cm. of water					TOTAL HEAD cm. of water					EFFECTIVE PRESSURE cm. of water				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
	5	4	3	2	1	5	4	3	2	1	5	4	3	2	1
		Test No. 12B													
2.1	-11	-9	-10	-5	-5	+2	+1	-2	0	-2	+37	+40	+47	+47	+53
3.0	-11	-8	-9	-5	-5	+2	+2	-1	0	-2	+37	+39	+46	+47	+53
5.0	-14	-11	-13	-8	-6	-1	-1	-5	-3	-3	+40	+42	+50	+50	+54
6.0	-15	-6	-9	-5	-5	-2	+4	-1	0	-2	+41	+37	+46	+47	+53
7.2	-25	-8	-9	-5	-5	-12	+2	-1	0	-2	+51	+39	+46	+47	+53
8.1	-44	-18	-13	-8	-8	-31	-8	-5	-3	-5	+70	+49	+50	+50	+56
10.4	-88	-23	-11	-6	-4	-75	-13	-3	-1	-1	+114	+54	+48	+48	+52
12.0	-262	-82	-55	-14	-8	-249	-72	-47	-9	-5	+288	+113	+92	+56	+56
13.5	-294	-110	-74	-16	-8	-281	-100	-66	-11	-5	+320	+141	+111	+58	+56
23.5	-392	-155	-127	-40	-14	-379	-145	-119	-35	-9	+418	+186	+164	+82	+62
24.0	-392	-155	-127	-40	-14	-379	-145	-119	-35	-9	+418	+186	+164	+82	+62
		Test No. 12C													
1.1	-13	-10	-10	-6	-8	0	0	-2	-1	-5	+39	+41	+47	+48	+56
1.9	-14	-10	-10	-6	-8	-1	0	-2	-1	-5	+40	+41	+47	+48	+56
2.9	-14	-10	-10	-6	-8	-1	0	-2	-1	-5	+40	+41	+47	+48	+56
3.7	-14	-9	-10	-6	-8	-1	+1	-2	-1	-5	+40	+40	+47	+48	+56
6.4	-19	-8	-10	-6	-8	-6	+2	-2	-1	-5	+45	+39	+47	+48	+56
12.6	-297	-100	-74	-28	-8	-284	-90	-66	-23	-5	+323	+131	+111	+70	+56
19.4	-362	-142	-122	-48	-13	-349	-132	-114	-43	-10	+388	+173	+159	+90	+61
20.0	-368	-146	-126	-50	-15	-355	-136	-118	-45	-12	+394	+177	+163	+92	+63
21.0	-373	-151	-132	-53	-16	-360	-141	-124	-48	-13	+399	+182	+169	+95	+64
22.0	-373	-154	-134	-54	-16	-360	-144	-126	-49	-13	+399	+185	+171	+96	+64
23.0	-376	-154	-134	-54	-16	-363	-144	-126	-49	-13	+402	+185	+171	+96	+64
24.0	-364	-159	-139	-57	-16	-351	-149	-139	-52	-13	+390	+190	+176	+99	+64

TABLE (continued)
III(D)

TIME hr.	PIEZOMETRIC PRESSURE cm. of water					TOTAL HEAD cm. of water					EFFECTIVE PRESSURE cm. of water				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
	5	4	3	2	1	5	4	3	2	1	5	4	3	2	1
Test No. 12D															
5.8	-13	-8	-6	-5	-4	0	+2	+2	0	-1	+39	+39	+43	+47	+52
6.5	-14	-10	-8	-5	-4	-1	0	0	0	-1	+40	+41	+45	+47	+52
7.3	-19	-16	-9	-5	-4	-6	-6	-1	0	-1	+45	+47	+46	+47	+52
9.1	-39	-35	-29	-9	-4	-26	-25	-21	-4	-1	+66	+66	+66	+51	+52
10.6	-72	-64	-57	-15	-9	-59	-54	-49	-10	-6	+98	+95	+94	+57	+57
11.0	-82	-74	-65	-20	-10	-69	-64	-57	-15	-7	+108	+105	+102	+62	+58
12.0	-120	-106	-88	-20	-8	-107	-96	-80	-15	-5	+146	+137	+125	+62	+56
13.0	-159	-140	-112	-20	-8	-146	-130	-104	-15	-5	+185	+171	+149	+62	+56
13.5	-174	-156	-122	-23	-6	-161	-146	-114	-18	-1	+200	+187	+159	+65	+54
23.0	-280	-239	-193	-57	-24	-267	-229	-185	-52	-19	+206	+270	+230	+99	+72
23.5	-282	-242	-196	-67	-26	-269	-232	-188	-62	-21	+208	+273	+233	+109	+74
Test No. 12E															
4.7	-11	-8	-5	-5	-5	+2	+2	+3	0	0	+37	+39	+42	+47	+53
7.8	-28	-24	-15	-6	-5	-15	-14	-7	-1	0	+54	+55	+52	+48	+53
9.6	-45	-43	-30	-13	-5	-32	-33	-22	-8	0	+71	+74	+67	+55	+53
20.6	-239	-227	-180	-83	-28	-226	-217	-172	-78	-23	+265	+258	+217	+125	+76
21.4	-242	-229	-183	-69	-28	-229	-219	-175	-64	-23	+268	+260	+220	+111	+76
22.5	-244	-232	-185	-69	-28	-231	-222	-177	-64	-23	+270	+263	+222	+111	+76
23.4	-244	-233	-188	-73	-29	-231	-223	-180	-68	-24	+270	+264	+225	+115	+77

TABLE III(D) (continued)

TIME hr.	PIEZOMETRIC PRESSURE cm. of water					TOTAL HEAD cm. of water					EFFECTIVE PRESSURE cm. of water				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
	5	4	3	2	1	5	4	3	2	1	5	4	3	2	1
	Test No. 12F														
7.0	-15	-8	-3	-4	-5	-2	+2	+5	+1	-2	+41	+39	+40	+46	+53
17.5	-201	-190	-164	-79	-31	-188	-180	-156	-74	-28	+227	+221	+201	+121	+79
18.3	-213	-200	-174	-84	-33	-200	-190	-166	-79	-30	+239	+231	+211	+126	+81
19.5	-229	-216	-186	-93	-37	-216	-206	-178	-88	-34	+255	+247	+223	+135	+85
20.0	-232	-218	-189	-94	-37	-219	-208	-181	-89	-34	+258	+249	+226	+136	+85
20.5	-237	-222	-191	-96	-37	-224	-212	-183	-91	-34	+263	+253	+228	+138	+85
20.8	-239	-224	-194	-97	-37	-226	-214	-186	-92	-34	+265	+255	+231	+139	+85
22.3	-246	-230	-201	-101	-38	-233	-220	-193	-96	-35	+272	+261	+238	+143	+86
23.0	-251	-236	-207	-110	-44	-238	-226	-199	-105	-41	+277	+267	+244	+152	+92

TABLE III (E)

TOTAL HEAD AND EFFECTIVE PRESSURE DETERMINATIONS
FOR ALL OF TEST NO. 13

TIME hr.	PIEZOMETRIC PRESSURE cm. of water					TOTAL HEAD cm. of water					EFFECTIVE PRESSURE cm. of water				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
	5	4	3	2	1	5	4	3	2	1	5	4	3	2	1
	Test No. 13														
8.8	-9	-8	-4	-3	-1	+4	+2	+4	+2	+2	+74	+77	+80	+84	+88
20.5	-9	-8	-5	-4	-1	+4	+2	+3	+1	+2	+74	+77	+81	+85	+88
21.7	-11	-10	-5	-4	-3	+2	0	+3	+1	0	+76	+81	+81	+85	+90
23.1	-14	-11	-6	-4	-3	-1	-1	+2	+1	0	+79	+82	+82	+85	+90
24.5	-15	-11	-8	-5	-3	-2	-1	0	0	0	+80	+82	+84	+86	+90
25.7	-16	-13	-8	-5	-3	-3	-3	0	0	0	+81	+84	+84	+86	+90
28.0	-6	-5	-13	0	0	+7	+5	-5	+5	+3	+71	+76	+89	+81	+87
28.8	-10	-9	-15	-3	-4	+3	+1	-7	+2	-1	+75	+80	+91	+84	+91
44.5	-25	-18	-11	-8	-3	-12	-8	-3	-3	0	+90	+89	+87	+89	+90
47.2	-24	-16	-10	-8	-4	-11	-6	-2	-3	-1	+89	+87	+86	+89	+91
49.2	-24	-16	-10	-8	-4	-11	-6	-2	-3	-1	+89	+87	+86	+89	+91
51.5	-25	-16	-11	-8	-4	-12	-6	-3	-3	-1	+90	+87	+87	+89	+91
53.0	-29	-19	-13	-9	-4	-16	-9	-5	-4	-1	+94	+90	+89	+90	+91
55.2	-31	-19	-11	-8	-4	-18	-9	-3	-3	-1	+96	+90	+87	+89	+91
57.2	-34	-19	-13	-8	-4	-21	-9	-5	-3	-1	+99	+90	+89	+89	+91
68.5	-69	-34	-15	-9	-4	-56	-24	-7	-4	-1	+134	+105	+91	+90	+91
69.8	-73	-36	-16	-9	-4	-60	-26	-8	-4	-1	+138	+107	+92	+90	+91
72.0	-79	-40	-19	-10	-5	-66	-30	-11	-5	-2	+144	+111	+95	+91	+92
73.2	-79	-40	-18	-9	-5	-66	-30	-10	-4	-2	+144	+111	+94	+90	+92
74.6	-77	-39	-18	-9	-5	-64	-29	-10	-4	-2	+142	+110	+94	+90	+92

TABLE III(E) (continued)

TIME hr.	PIEZOMETRIC PRESSURE cm. of water					TOTAL HEAD cm. of water					EFFECTIVE PRESSURE cm. of water				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
	5	4	3	2	1	5	4	3	2	1	5	4	3	2	1
		Test No. 13A													
6.4	+4	+4	+8	+6	-4	+17	+14	+16	+11	-1	+61	+67	+68	+75	+91
8.2	+4	+1	+6	+5	-4	+17	+11	+14	+10	-1	+61	+70	+70	+76	+91
10.1	+1	0	+5	+5	-4	+16	+10	+13	+10	-1	+64	+71	+71	+76	+91
12.6	-1	-1	+3	+3	-4	+15	+9	+11	+8	-1	+66	+72	+73	+78	+91
23.5	-24	0	-4	-3	-4	-11	+10	+4	+2	-1	+89	+71	+80	+84	+91
25.4	-33	-5	-5	-4	-4	-22	+5	+3	-1	-1	+98	+76	+81	+85	+91
26.2	-42	-11	-10	-8	-5	-29	-1	-2	-3	-2	+107	+82	+86	+89	+92
27.0	-44	-11	-10	-6	-4	-31	-1	-2	-1	-1	+109	+82	+86	+87	+91
28.2	-47	-14	-10	-6	-4	-34	-4	-2	-1	-1	+112	+85	+86	+87	+91
29.1	-54	-31	-14	-9	-5	-41	-21	-6	-4	-2	+119	+102	+90	+90	+92
29.8	-68	-42	-23	-15	-10	-55	-32	-15	-10	-7	+133	+113	+99	+96	+97
32.0	-73	-43	-21	-11	-6	-60	-33	-13	-6	-3	+138	+114	+97	+92	+93
34.3	-87	-50	-26	-13	-8	-74	-40	-18	-8	-5	+152	+121	+102	+94	+95
35.0	-91	-53	-29	-14	-8	-78	-43	-21	-9	-5	+156	+124	+105	+95	+95
36.1	-97	-55	-30	-14	-8	-84	-45	-22	-9	-5	+162	+126	+106	+95	+95
38.1	-111	-63	-35	-14	-8	-98	-53	-27	-9	-5	+176	+134	+111	+95	+95
47.5	-178	-94	-50	-18	-9	-165	-84	-42	-13	-6	+243	+165	+126	+99	+96
48.5	-182	-96	-52	-18	-9	-169	-86	-44	-13	-6	+247	+167	+128	+99	+96
49.6	-186	-99	-50	-16	-9	-173	-89	-42	-11	-6	+251	+170	+126	+97	+96
50.5	-192	-102	-52	-16	-9	-179	-92	-44	-11	-6	+257	+173	+128	+97	+96
52.5	-208	-113	-59	-19	-10	-195	-103	-51	-14	-7	+273	+184	+136	+100	+97
53.5	-210	-113	-59	-19	-9	-198	-103	-51	-14	-6	+275	+184	+136	+100	+96
54.5	-218	-116	-62	-20	-10	-205	-106	-54	-15	-7	+283	+187	+138	+101	+97
55.5	-224	-120	-64	-21	-11	-211	-110	-56	-16	-8	+289	+191	+140	+102	+98
59.7	-233	-125	-67	-21	-9	-220	-115	-59	-16	-6	+298	+196	+143	+102	+96

TABLE III(E) (continued)

TIME hr. (1)	PIEZOMETRIC PRESSURE cm. of water (2)	(3)	(4)	(5)	(6)	TOTAL HEAD cm. of water (7)	(8)	(9)	(10)	(11)	EFFECTIVE PRESSURE cm. of water (12)	(13)	(14)	(15)	(16)
	5	4	3	2	1	5	4	3	2	1	5	4	3	2	1
62.1	-250	-135	-77	-26	-13	-237	-125	-69	-21	-10	+315	+206	+153	+107	+100
71.5	-229	-120	-71	-21	-9	-216	-110	-63	-16	-6	+294	+191	+147	+102	+96
72.5	-225	-119	-69	-21	-9	-212	-109	-61	-16	-6	+290	+190	+145	+102	+96
73.5	-220	-116	-67	-20	-9	-207	-106	-59	-15	-6	+285	+187	+143	+101	+96
74.5	-225	-120	-72	-24	-10	-212	-110	-64	-19	-7	+290	+191	+148	+105	+97
76.2	-223	-122	-67	-20	-9	-210	-112	-59	-15	-6	+288	+193	+143	+101	+96
77.5	-246	-137	-77	-26	-13	-233	-127	-69	-21	-10	+311	+208	+153	+107	+100
78.5	-248	-137	-76	-25	-13	-235	-127	-68	-20	-10	+313	+208	+152	+106	+100
79.8	-252	-137	-74	-23	-9	-239	-127	-66	-18	-6	+317	+208	+150	+104	+96
95.8	-281	-146	-88	-26	-10	-268	-136	-80	-21	-7	+346	+217	+164	+107	+97
98.1	-295	-156	-91	-26	-10	-282	-146	-83	-21	-7	+360	+227	+167	+107	+ 97
100.2	-331	-181	-102	-31	-11	-318	-171	-94	-26	-8	+396	+252	+178	+112	+98
101.4	-353	-194	-107	-33	-14	-340	-184	-99	-28	-11	+418	+265	+183	+114	+101
102.5	-373	-204	-113	-34	-14	-360	-194	-105	-29	-11	+438	+275	+189	+115	+101
103.5	-396	-214	-120	-37	-13	-383	-204	-112	-32	-10	+464	+285	+196	+118	+100
107.6	-459	-240	-123	-37	-10	-446	-230	-115	-32	-7	+524	+311	+199	+118	+97
108.0	-478	-256	-135	-45	-20	-465	-246	-127	-40	-17	+543	+327	+211	+126	+107
108.8	-480	-251	-125	-35	-9	-467	-241	-117	-30	-6	+545	+322	+201	+116	+96
	Test No. 13B														
6.5	-3	0	+1	+1	0	+10	+10	+9	+6	+3	+68	+71	+75	+80	+87
10.0	-11	-6	-1	0	0	+2	+4	+7	+5	+3	+76	+77	+77	+81	+87
12.0	-16	-10	-4	-3	-1	-3	0	+3	+2	+2	+81	+81	+80	+84	+88
22.1	-94	-48	-20	-10	-5	-81	-38	-12	-5	-2	+159	+119	+96	+91	+92
23.1	-113	-60	-26	-14	-8	-100	-50	-18	-9	-5	+178	+131	+102	+95	+95
24.0	-123	-67	-26	-11	-5	-110	-57	-18	-6	-2	+188	+138	+102	+92	+92
25.2	-142	-79	-34	-14	-5	-129	-69	-26	-9	-2	+207	+150	+110	+95	+92

TABLE III(E) (continued)

TIME hr. (1)	PIEZOMETRIC PRESSURE cm. of water (2)	(3)	(4)	(5)	(6)	TOTAL HEAD cm. of water (7)	(8)	(9)	(10)	(11)	EFFECTIVE PRESSURE cm. of water (12)	(13)	(14)	(15)	(16)
	5	4	3	2	1	5	4	3	2	1	5	4	3	2	1
26.6	-170	-98	-42	-18	-8	-157	-88	-34	-13	-5	+235	+169	+118	+99	+95
27.7	-189	-111	-47	-19	-8	-176	-101	-39	-14	-5	+254	+182	+123	+100	+95
29.0	-214	-125	-54	-20	-8	-201	-115	-46	-15	-5	+279	+196	+130	+101	+95
30.6	-240	-141	-62	-23	-8	-227	-131	-54	-18	-5	+305	+212	+138	+104	+95
34.0	-290	-169	-77	-28	-11	-277	-159	-69	-23	-8	+355	+240	+153	+109	+98
35.0	-297	-170	-77	-25	-8	-284	-160	-69	-20	-5	+362	+241	+153	+106	+95
36.0	-309	-177	-82	-28	-11	-296	-167	-74	-23	-8	+374	+248	+158	+109	+98
46.0	-350	-190	-83	-28	-10	-337	-180	-75	-23	-7	+415	+261	+159	+109	+97
47.3	-358	-194	-86	-29	-11	-345	-184	-78	-24	-8	+423	+265	+162	+110	+98
49.4	-368	-199	-86	-29	-11	-355	-189	-78	-24	-8	+433	+270	+162	+110	+98
52.0	-384	-209	-92	-31	-13	-371	-199	-84	-26	-10	+449	+280	+168	+112	+100
54.5	-383	-202	-86	-26	-9	-370	-192	-78	-21	-6	+448	+273	+162	+107	+96
57.2	-392	-208	-94	-30	-10	-379	-198	-86	-25	-7	+457	+279	+170	+111	+97
70.0	-394	-202	-101	-31	-10	-381	-192	-93	-26	-7	+459	+273	+177	+112	+97
76.3	-398	-208	-105	-31	-10	-385	-198	-97	-26	-7	+463	+279	+181	+112	+97
78.5	-408	-217	-113	-37	-11	-395	-207	-105	-32	-8	+473	+288	+189	+118	+98
83.0	-422	-222	-117	-37	-11	-409	-212	-109	-32	-8	+487	+293	+193	+118	+98
97.3	-417	-209	-116	-35	-11	-404	-199	-108	-30	-8	+482	+280	+192	+116	+98
99.0	-437	-232	-122	-38	-11	-424	-222	-114	-33	-8	+502	+303	+198	+119	+98
100.5	-472	-262	-133	-39	-11	-459	-252	-125	-34	-8	+537	+333	+209	+120	+98
101.5	-499	-288	-144	-44	-14	-486	-278	-136	-39	-11	+564	+359	+220	+125	+101
104.7	-575	-345	-144	-45	-14	-562	-335	-136	-40	-11	+640	+416	+220	+126	+101
107.8	-624	-372	-181	-47	-14	-611	-362	-173	-42	-11	+689	+443	+257	+128	+101
110.0	-641	-380	-186	-47	-14	-628	-370	-178	-42	-11	+705	+451	+262	+128	+101
110.2	-642	-380	-188	-47	-14	-629	-370	-180	-42	-11	+706	+451	+264	+128	+101
118.2	-622	-380	-191	-47	-13	-609	-370	-183	-42	-10	+687	+451	+267	+128	+100

TABLE III(E) (continued)

TIME hr. (1)	PIEZOMETRIC PRESSURE cm. of water (2)	(3)	(4)	(5)	(6)	TOTAL HEAD cm. of water (7)	(8)	(9)	(10)	(11)	EFFECTIVE PRESSURE cm. of water (12)	(13)	(14)	(15)	(16)
	5	4	3	2	1	5	4	3	2	1	5	4	3	2	1
	Test No. 13C														
20.6	-116	-67	-25	-11	-4	-103	-57	-17	-6	-1	+181	+138	+101	+92	+91
22.0	-133	-81	-33	-14	-6	-120	-71	-25	-9	-3	+198	+152	+109	+95	+92
23.6	-156	-99	-45	-21	-13	-143	-89	-37	-16	-10	+221	+170	+121	+102	+100
25.5	-180	-113	-54	-24	-13	-167	-103	-46	-19	-10	+245	+184	+130	+105	+100
27.5	-203	-126	-63	-24	-11	-190	-116	-55	-19	-8	+268	+197	+139	+105	+98
29.1	-216	-135	-66	-24	-9	-203	-125	-58	-19	-6	+281	+206	+142	+105	+96
33.0	-238	-156	-81	-30	-13	-225	-146	-73	-25	-10	+303	+227	+157	+111	+100
44.6	-311	-196	-99	-32	-9	-298	-186	-91	-27	-6	+376	+267	+175	+113	+96
47.5	-322	-204	-102	-33	-10	-309	-194	-94	-28	-7	+387	+275	+178	+114	+97
50.7	-335	-212	-106	-34	-10	-322	-202	-98	-29	-7	+400	+283	+182	+115	+97
53.0	-354	-223	-113	-38	-14	-341	-213	-105	-33	-11	+419	+294	+189	+119	+101
56.5	-366	-225	-115	-37	-10	-353	-215	-107	-32	-7	+431	+296	+191	+118	+97
68.5	-325	-198	-106	-35	-10	-312	-188	-98	-30	-7	+390	+269	+182	+116	+97
69.3	-316	-191	-101	-32	-8	-303	-181	-93	-27	-5	+381	+262	+177	+113	+95
73.2	-353	-214	-113	-39	-11	-340	-204	-105	-34	-8	+418	+285	+189	+120	+98
75.1	-365	-220	-116	-39	-11	-352	-210	-108	-34	-8	+430	+291	+192	+120	+98
76.2	-372	-224	-117	-39	-11	-359	-214	-109	-34	-8	+437	+295	+193	+120	+98
77.1	-382	-232	-122	-42	-13	-369	-222	-114	-37	-10	+447	+303	+198	+123	+100
79.0	-410	-246	-128	-44	-13	-397	-236	-120	-39	-10	+475	+317	+204	+125	+100
81.0	-443	-263	-137	-48	-13	-430	-253	-129	-43	-10	+508	+334	+213	+129	+100
82.0	-458	-272	-142	-50	-14	-445	-262	-134	-45	-11	+523	+343	+218	+131	+101
83.0	-479	-281	-146	-50	-13	-466	-271	-138	-45	-10	+544	+352	+222	+131	+100
84.0	-500	-292	-150	-50	-13	-487	-282	-142	-45	-10	+565	+363	+226	+131	+100
85.0	-510	-306	-155	-50	-13	-497	-296	-147	-45	-10	+575	+377	+231	+131	+100

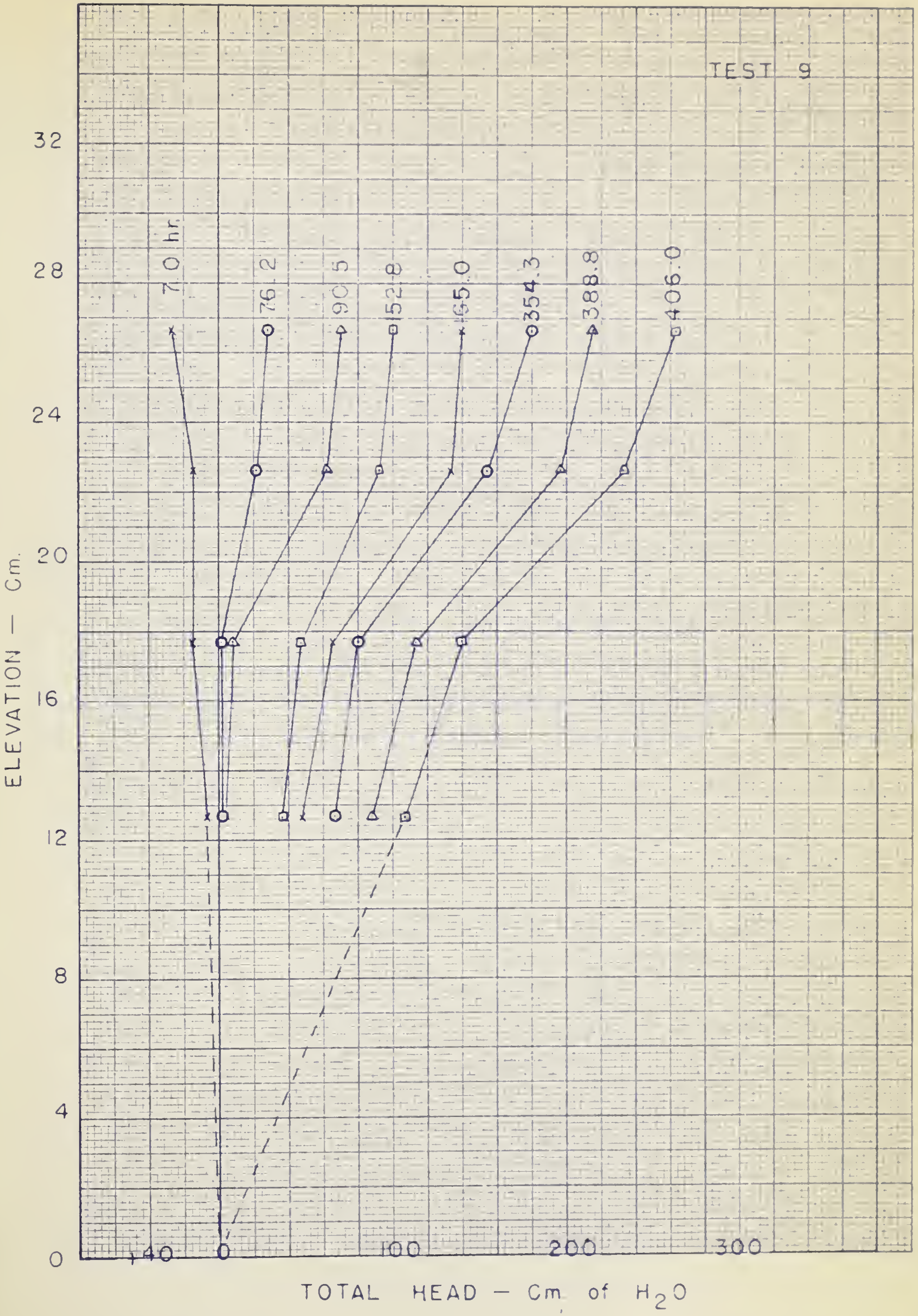

TEST 9
7.0 hr.
76.2
90.5
152.8
165.0
354.3
388.8
406.0
ELEVATION — Cm.
32
28
24
20
16
12
8
4
0
-40
0
100
200
300
TOTAL HEAD — Cm of H_2O

PLATE 21A

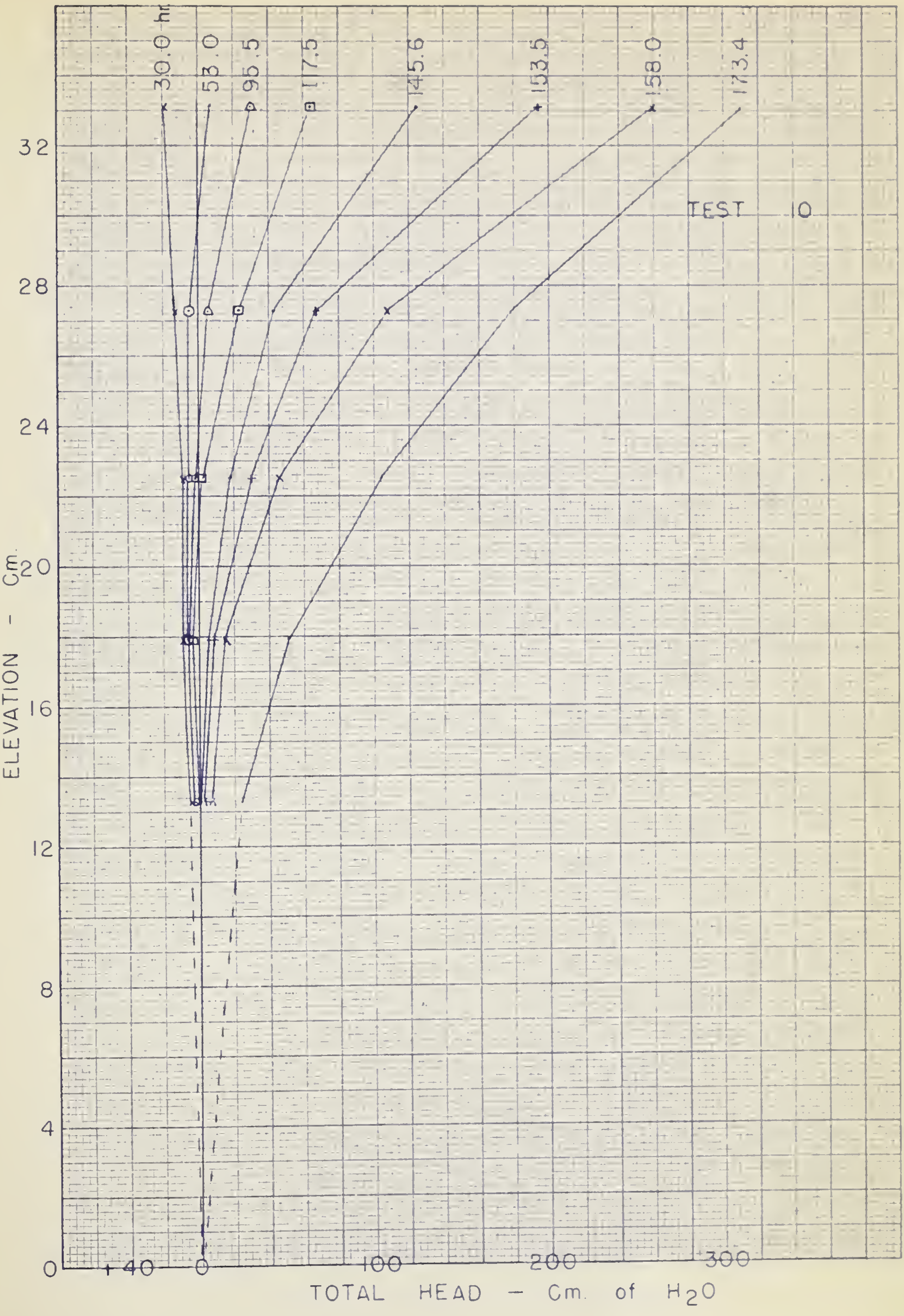

30.0 hr
53.0
95.5
117.5
145.6
153.5
158.0
173.4
TEST 10
32
28
24
20
16
12
8
4
0
ELEVATION - Cm.
+40
0
100
200
300
TOTAL HEAD - Cm. of H_2O

PLATE 21 B

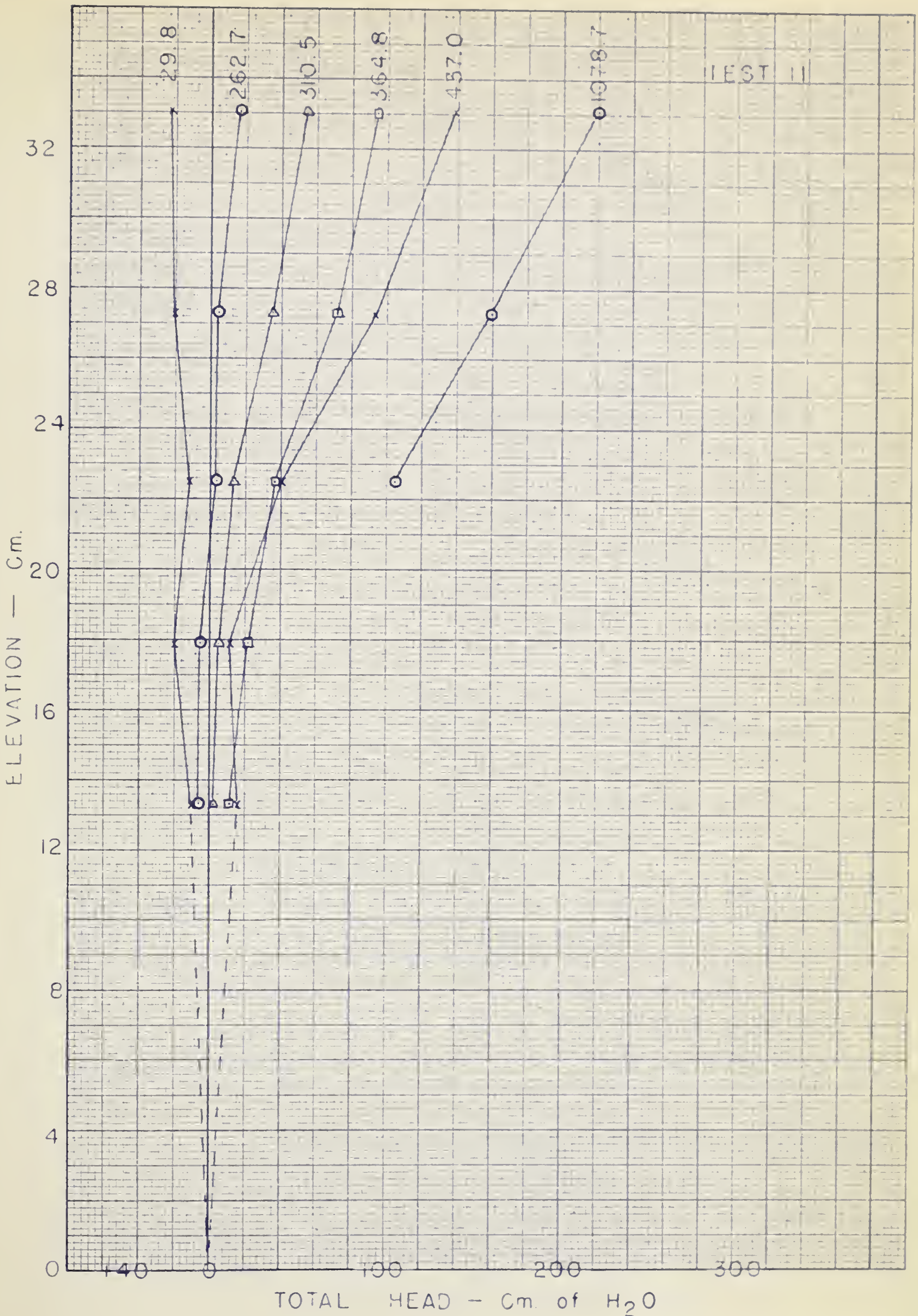

29.8
262.7
310.5
364.8
457.0
1078.7
TEST 11
ELEVATION — Cm.
32
28
24
20
16
12
8
4
0
-100
0
100
200
300
TOTAL HEAD — Cm. of H_2O

PLATE 21C

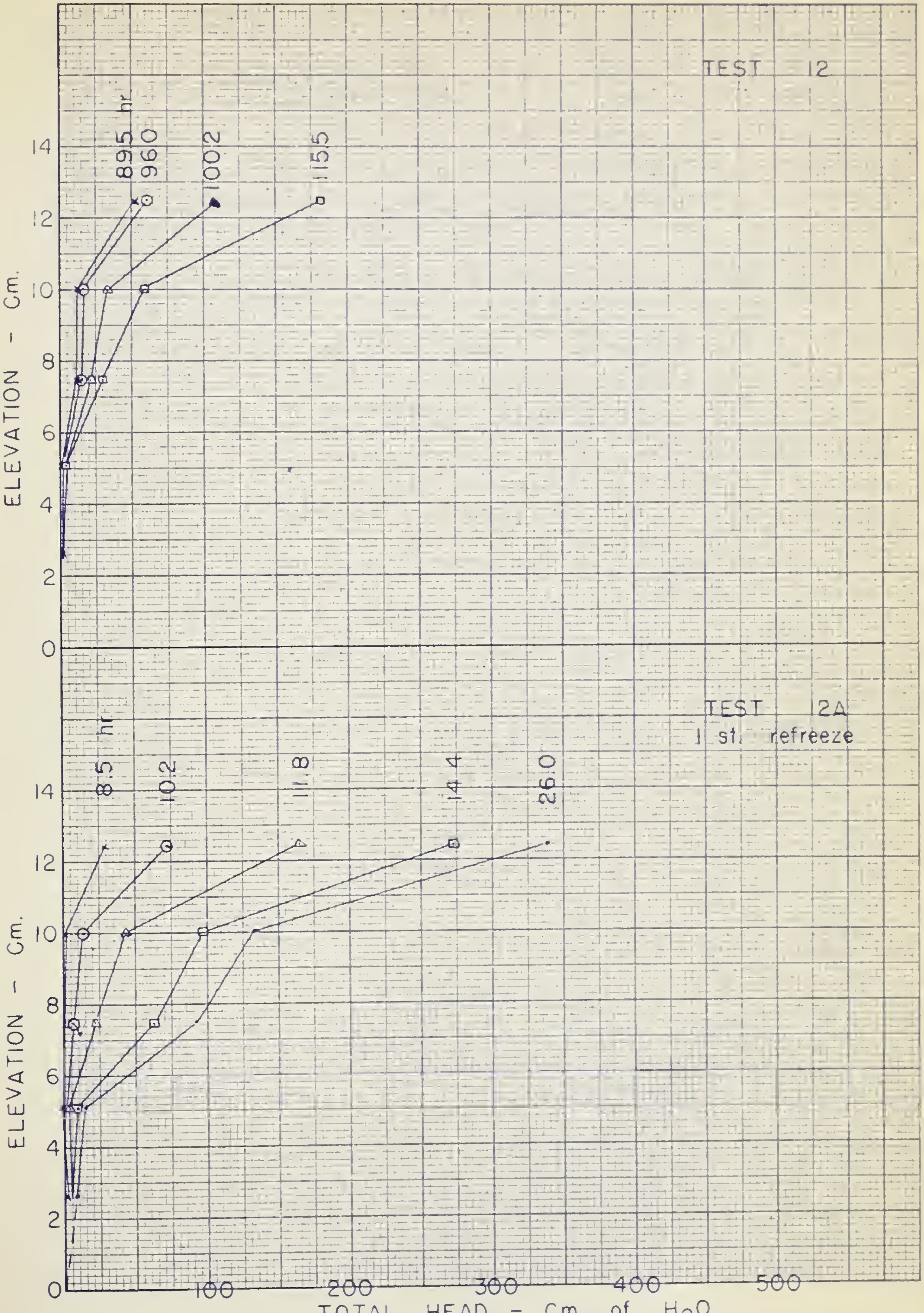

TEST 12
8.95 hr
9.60
10.02
11.55
TEST 12A
1 st. refreeze
8.5 hr
10.2
11.8
14.4
26.0
ELEVATION - Cm.
0
2
4
6
8
10
12
14
100
200
300
400
500
TOTAL HEAD - Cm. of H_2O

PLATE 21D

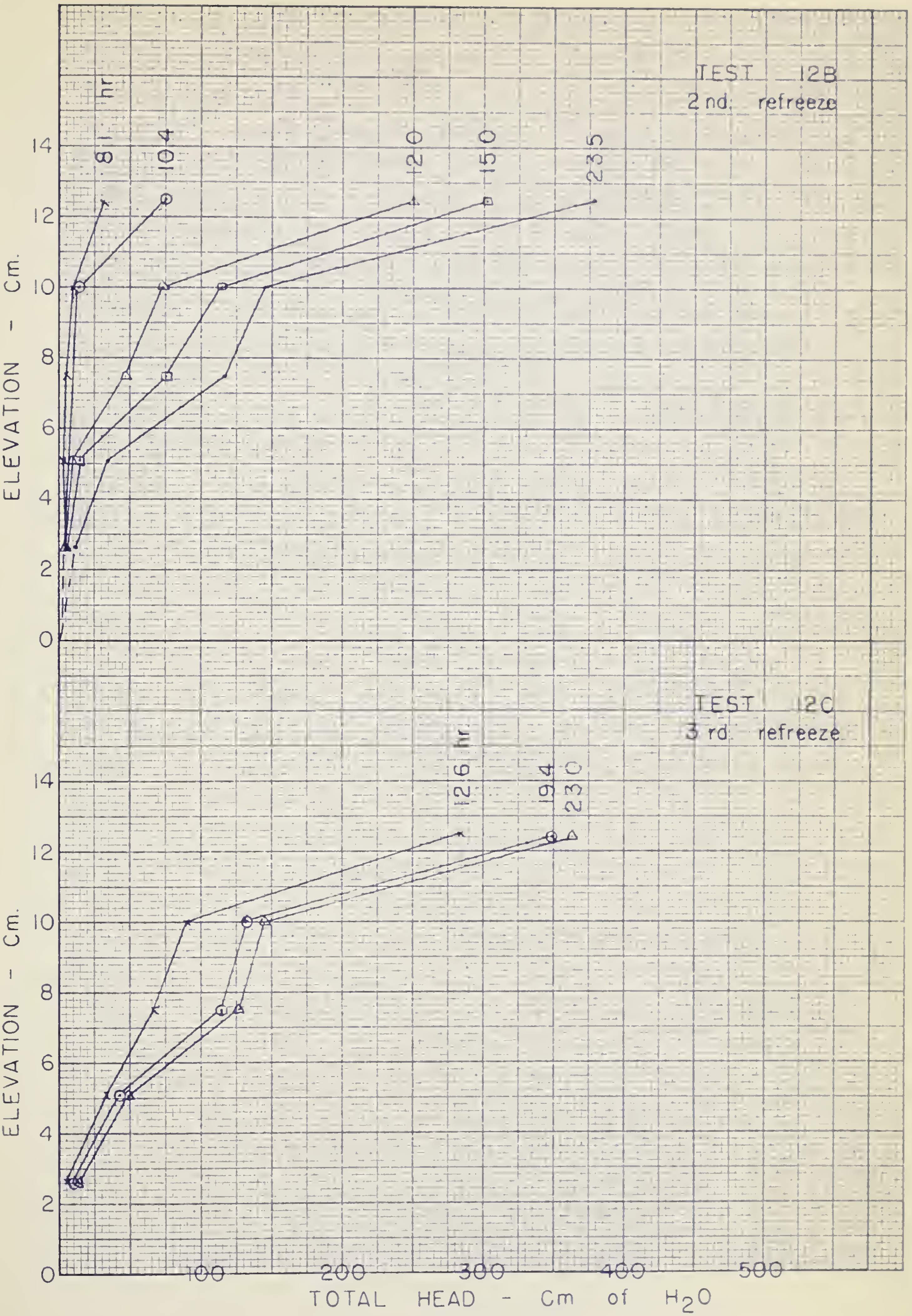

TEST 12B
2 nd refreeze
81 hr
104
120
150
235
ELEVATION - Cm.
14
12
10
8
6
4
2
0
TEST 12C
3 rd refreeze
126 hr
194
230
ELEVATION - Cm.
14
12
10
8
6
4
2
0
100
200
300
400
500
TOTAL HEAD - Cm of H_2O

PLATE 21E

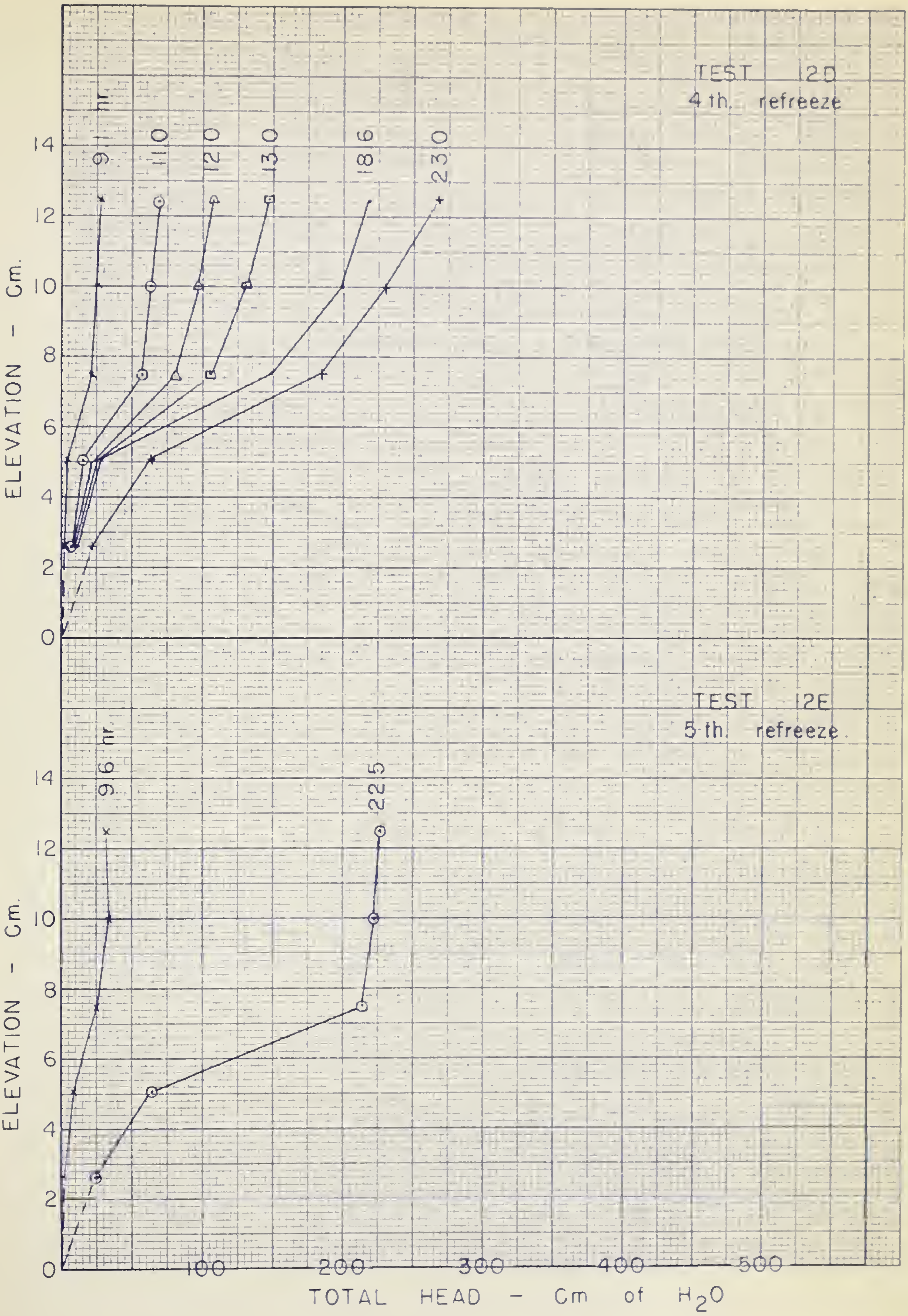

TEST 12D
4 th. refreeze
91 hr.
110
120
130
186
230
TEST 12E
5 th. refreeze
96 hr.
225
ELEVATION - Cm.
ELEVATION - Cm.
0
2
4
6
8
10
12
14
100
200
300
400
500
TOTAL HEAD - Cm of H_2O

PLATE 21F

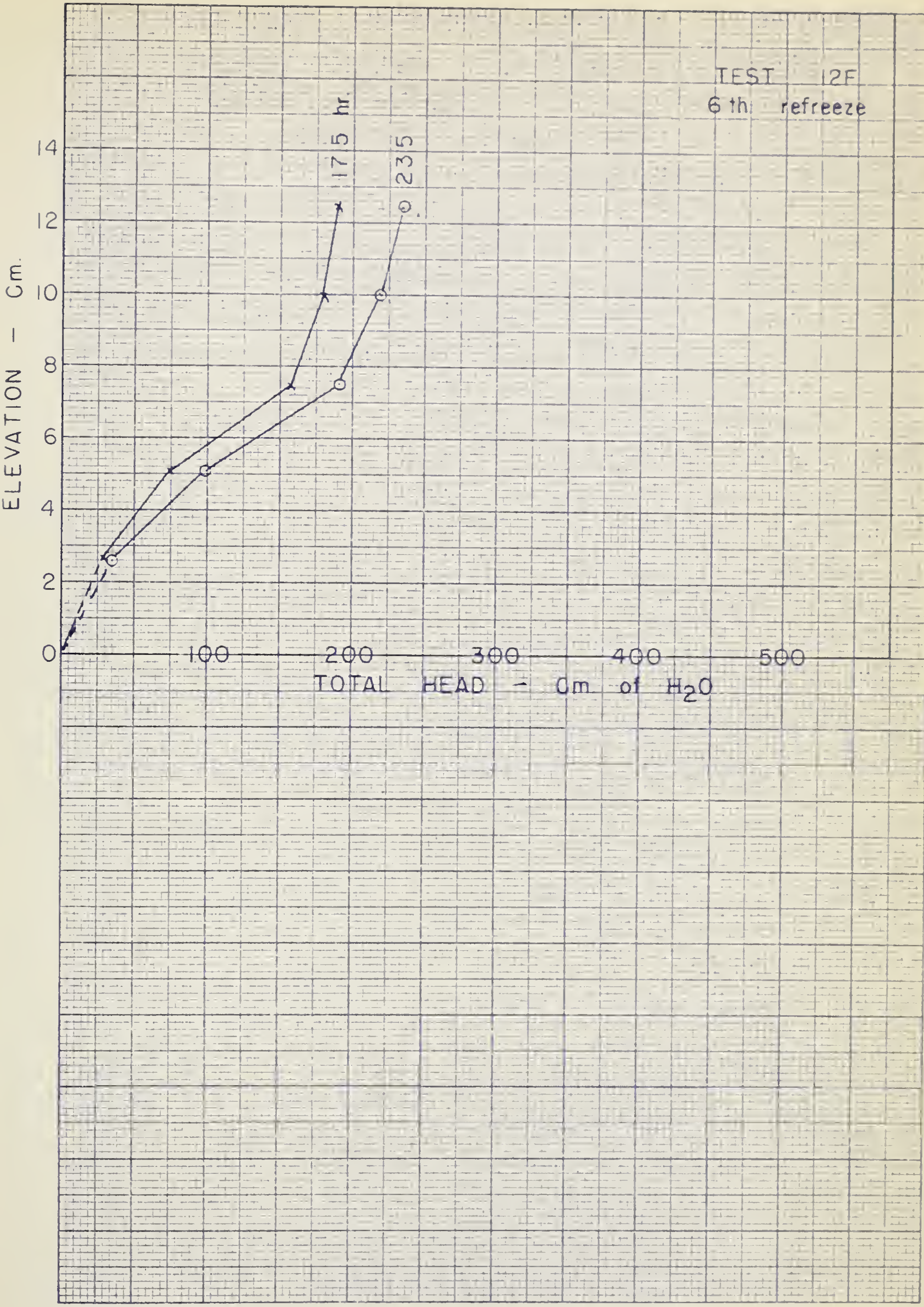

TEST 12F
6 th refreeze
17.5 hr.
23.5
ELEVATION - Cm.
0
2
4
6
8
10
12
14
100
200
300
400
500
TOTAL HEAD - Cm of H_2O

PLATE 21G

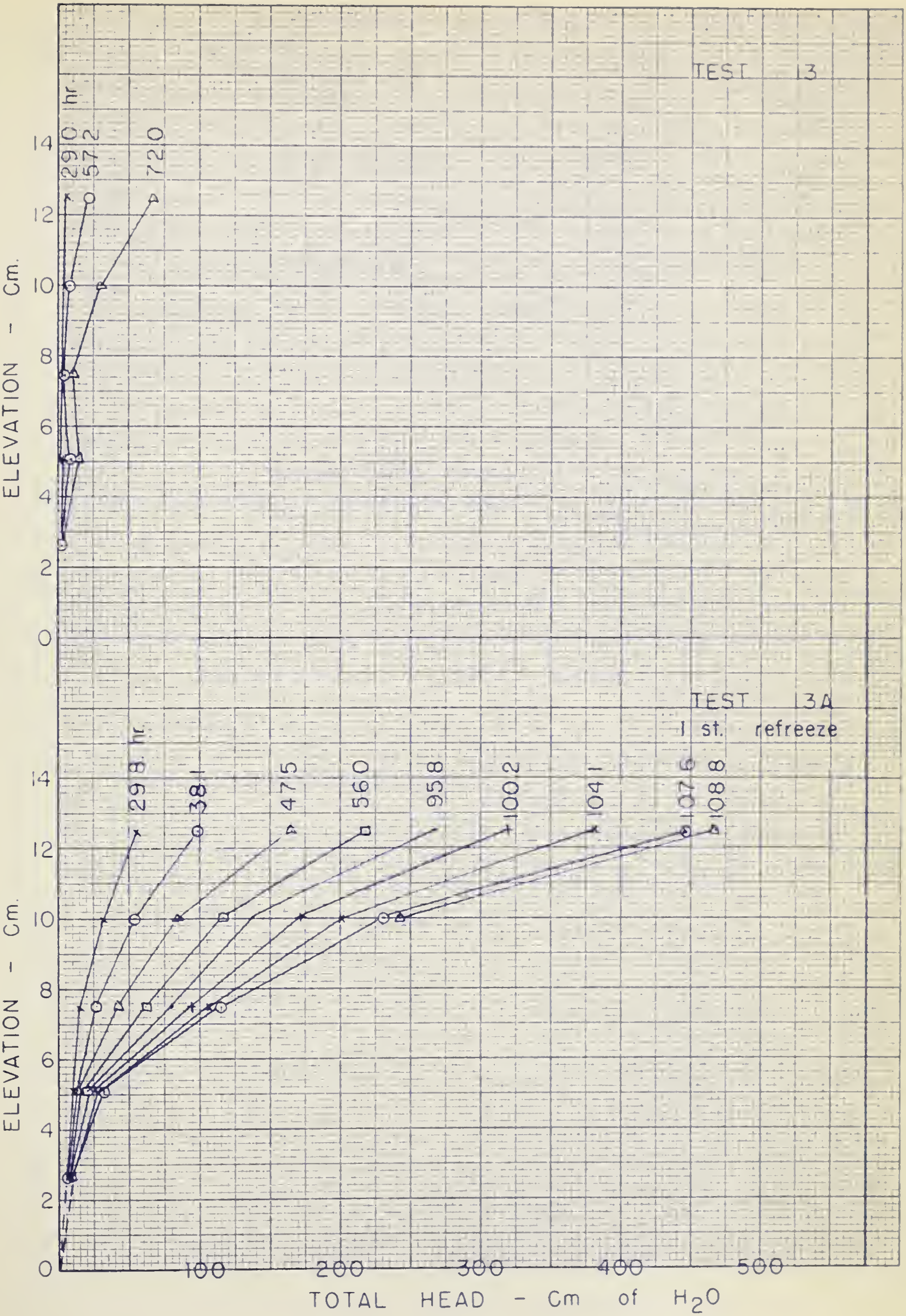

TEST 13
290 hr.
572
720
ELEVATION - Cm.
TEST 13A
1 st. refreeze
298 hr.
381
475
560
958
1002
1041
1076
1088
ELEVATION - Cm.
TOTAL HEAD - Cm of H_2O

PLATE 21 H

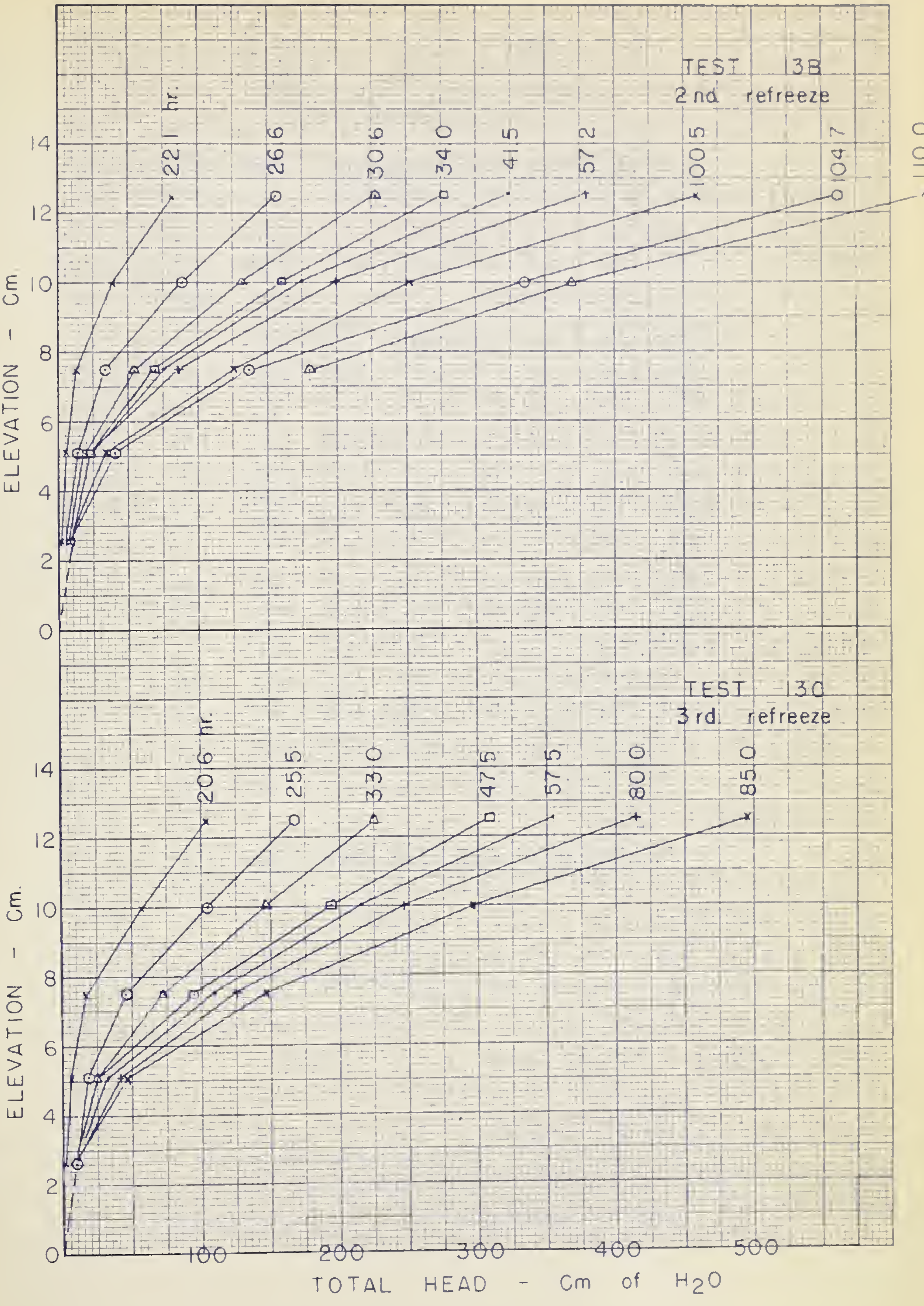

TEST 13B
2nd refreeze
22.1 hr.
26.6
30.6
34.0
41.5
57.2
100.5
104.7
110.0
TEST 13C
3rd refreeze
20.6 hr.
25.5
33.0
47.5
57.5
80.0
85.0
ELEVATION - Cm
ELEVATION - Cm.
0
2
4
6
8
10
12
14
100
200
300
400
500
TOTAL HEAD - Cm of H_2O

PLATE 21 J

TABLE IV (D)

TEMPERATURE FROM STRIP CHARTS
TESTS 12-12E

TEST	TIME hr.	ELEVATION ABOVE RESERVOIR - cm. 19.2	16.7	14.1	11.6	9.0	6.5
12	89.5	29.4	36.0	39.6	43.2	46.5	48.3
"	96.0	28.1	37.0	41.0	44.7	47.8	49.4
12A	8.5	32.0	37.4	41.4	45.3	49.0	51.3
"	10.2	30.7	36.3	40.4	44.2	48.0	50.2
"	11.8	29.2	35.5	39.4	43.2	47.1	49.3
"	14.4	25.2	33.5	37.8	42.0	45.9	48.2
"	26.0	15.7	24.0	30.0	37.0	41.9	44.8
12B	8.1	32.0	37.5	41.7	45.8	49.2	51.4
"	10.4	29.9	36.5	40.8	44.8	48.5	50.5
"	12.0	27.5	35.3	40.0	44.3	48.0	50.2
"	15.0	22.5	32.0	37.6	42.4	46.8	49.3
"	23.5	13.3	22.3	29.1	36.1	41.8	44.8
12C	12.6	23.9	33.4	38.0	42.6	47.0	49.5
"	19.4	13.4	23.3	30.3	36.9	42.2	45.3
"	23.0	10.6	20.2	27.4	34.5	40.3	43.8
12D	9.1	32.4	38.0	42.6	47.4	50.4	
"	11.0	30.5	36.4	40.8	45.3	48.5	
"	12.0	29.0	35.8	40.0	44.6	47.8	
"	13.0	27.2	34.8	39.1	43.8	47.0	
"	18.6	17.0	27.4	34.5	40.5	44.0	
"	23.0	11.0	20.9	29.0	36.8	41.0	
12E	9.6	30.8	35.8	40.1	44.2	47.4	
"	22.5	18.5	25.9	32.0	37.8	41.5	

TABLE IV (E)

TEMPERATURES FROM STRIP CHARTS
TESTS 13-13C

TIME	ELEVATION ABOVE RESERVOIR WATER SURFACE - cm.										
hr.	37.0	34.5	31.9	29.4	26.8	24.3	21.8	19.2	16.7	11.6	6.5
	Test 13										
29.0	28.8	35.1	40.0	43.3	46.5	49.3	52.0	54.0	55.8	59.0	61.5
57.2	14.8	23.5	28.4	32.6	37.2	40.9	44.8	47.8	51.7	55.2	57.7
72.0	15.2	23.5	28.0	31.2	36.4	40.3	44.2	47.2	51.4	55.0	57.5
	Test 13A										
29.8	14.2	22.1	28.8	33.8	38.5	42.3	45.6	48.0	50.8	53.6	55.6
38.1	-4.0	2.1	13.1	21.5	29.1	35.6	40.4	43.2	47.8	51.9	54.3
47.5	-5.7	-0.3	9.9	17.6	26.5	31.0	36.9	41.4	46.0	51.1	54.1
56.0	-6.0	-9.9	9.0	16.2	21.9	31.7	35.6	40.2	44.7	50.0	53.1
95.8	-14.4	-12.0	-8.6	-2.5	8.4	18.0	25.8	32.6	39.5	47.0	51.5
100.2	-18.4	-17.0	-15.0	-11.3	-4.2	4.5	14.9	25.9	35.9	45.2	50.8
104.1	-18.8	-17.5	-15.6	-12.2	-5.6	2.2	12.1	23.4	32.5	43.4	49.7
107.6	-19.1	-17.1	-16.2	-13.0	-6.6	1.2	10.4	21.8	31.2	42.0	48.8
108.8	-19.0	-18.5	-16.0	-13.0	-6.6	1.0	10.4	21.4	30.8	41.0	48.6
	Test 13B										
22.1	8.0	18.0	24.5	31.4	34.9		42.6	46.0	47.8	50.5	52.2
26.6	5.4	14.9	21.0	27.5	32.3		41.0	44.5	46.7	49.5	51.4
30.6	1.8	11.3	17.9	24.5	29.7		39.2	43.1	45.5	48.5	50.6
34.0	1.0	10.0	16.3	22.8	27.8		38.0	42.1	44.9	47.8	50.2
41.5	-0.4	8.2	14.4	20.4	25.3		35.8	40.5	43.3	46.9	49.4
57.2	-9.5	-4.2	3.4	11.0	18.0		30.5	36.0	39.8	44.5	47.6
100.5	-19.7	-18.0	-16.8	-13.5	-9.8		10.0	19.5	27.8	37.8	43.5
104.7	-20.1	-18.8	-17.5	-14.2	-10.6		8.4	17.6	25.8	36.6	43.0
110.0	-19.9	-18.5	-17.2	-14.2	-10.7		7.6	16.8	24.4	35.8	42.6
	Test 13C										
20.6	16.8	27.1	35.0	38.0	42.0	45.9	47.2	49.3	50.6	52.5	53.0
25.5	11.4	22.5	30.2	35.0	39.4	44.0	45.5	47.8	49.5	51.6	52.5
33.0	8.0	18.1	26.1	30.5	35.7	41.0	42.7	45.4	47.3	50.0	51.0
47.5	-9.2	-4.0	4.6	15.3	24.0	35.8	38.0	42.0	44.9	48.9	50.3
57.5	-17.1	-15.0	-12.1	-7.5	-1.2	17.2	22.5	30.2	35.7	44.9	48.5
80.0	-19.0	-17.5	-15.6	-12.7	-9.5	0.8	11.8	20.5	26.4	38.7	43.7
85.0	-19.5	-18.5	-17.5	-15.8	-13.9	-10.7	-1.8	5.2	14.8	35.3	41.8

[illegible]

TABLE IV(A)

TEMPERATURES FROM STRIP CHARTS
TEST 9

TIME	ELEVATION ABOVE RESERVOIR WATER SURFACE - cm.													
hr.	60.5	58.0	55.4	52.9	50.3	47.8	45.3	42.7	40.2	35.1	27.5	19.9	12.2	1.4
7.0	38.0	41.0	47.4	50.7	54.5	57.5	60.0	62.0	63.4	65.4	66.8	67.6	68.5	68.7
76.2	16.0	17.8	21.7	23.7	26.4	28.9	31.4	33.1	34.5	37.2	42.7	47.8	52.4	58.0
90.5	14.7	16.0	19.6	21.8	24.0	26.1	28.5	30.6	32.8	36.4	42.9	48.3	53.0	58.9
152.8	13.5	15.0	18.8	21.0	23.4	25.8	28.0	30.0	32.5	37.0	44.1	49.9	54.3	59.4
165.0	14.2	16.0	19.5	21.5	23.6	25.7	27.8	29.9	32.1	36.5	43.6	49.3	54.0	60.3
354.3	6.4	8.5	13.2	16.0	19.5	22.3	25.2	28.2	31.5	36.7	44.4	50.5	55.3	60.3
388.8	5.8	8.2	13.0	15.8	19.2	22.0	25.0	27.8	31.0	36.6	44.2	50.5	55.1	59.8
406.0	5.6	8.7	12.2	15.2	18.6	21.4	24.5	27.3	30.5	36.1	43.8	50.0	54.7	59.3

NOTE: The temperatures listed were taken directly from the strip charts at the times indicated and do not include a calibration factor. Units are degrees Fahrenheit.

TABLE IV (B)

TEMPERATURES FROM STRIP CHARTS
TEST 10

TIME	ELEVATION ABOVE RESERVOIR WATER SURFACE - cm.										
hr.	61.0	57.9	55.3	52.8	47.7	42.6	37.6	29.9	22.2	14.6	7.7
30.0	15.0	21.4	24.2	26.0	31.6	35.2	38.3	45.1	50.2	55.3	61.3
53.0	13.0	18.1	20.6	22.0	27.0	31.2	35.0	43.8	50.2	56.7	64.3
95.5	8.8	14.5	17.7	19.7	25.5	30.4	34.3	43.9	50.5	57.0	64.2
117.5	8.0	13.4	16.6	18.5	24.3	29.0	32.3	41.2	47.8	54.0	60.8
145.6	-10.2	-0.5	4.9	8.7	17.6	25.2	30.2	38.9	46.3	53.0	59.8
153.5	-10.4	-1.8	3.4	7.0	15.7	23.4	28.6	37.7	45.4	52.5	58.4
158.0	-11.2	-2.2	2.8	6.1	15.0	22.3	28.0	37.0	45.0	51.9	59.0
173.4	-11.4	-3.0	1.6	5.0	13.5	20.9	26.3	36.2	44.5	52.0	59.1

TABLE IV(C)

TEMPERATURES FROM STRIP CHARTS
TEST 11

TIME	ELEVATION ABOVE RESERVOIR WATER SURFACE - cm.										
hr.	61.0	57.9	55.3	52.8	47.7	42.6	37.6	29.9	22.2	14.6	7.7
29.8	19.9	26.5	29.2	30.8	35.8	38.8	41.8	46.7	51.2	56.4	61.4
262.7	4.8	14.8	20.2	24.3	34.0	39.3	43.0	49.0	53.0	57.0	60.8
301.5	3.7	13.0	18.2	22.5	32.0	36.8	40.9	46.8	51.0	55.1	58.5
364.8	-4.5	6.0	12.3	18.0	29.8	35.0	39.6	46.3	51.1	55.6	59.4
437.0	-22.2	-8.0	0.0	8.0	24.2	31.5	37.2	45.2	50.7	55.0	58.3
1078.8	-22.3	-10.8	-4.8	3.0	16.8	25.0	32.2	40.5	46.4	51.5	56.1

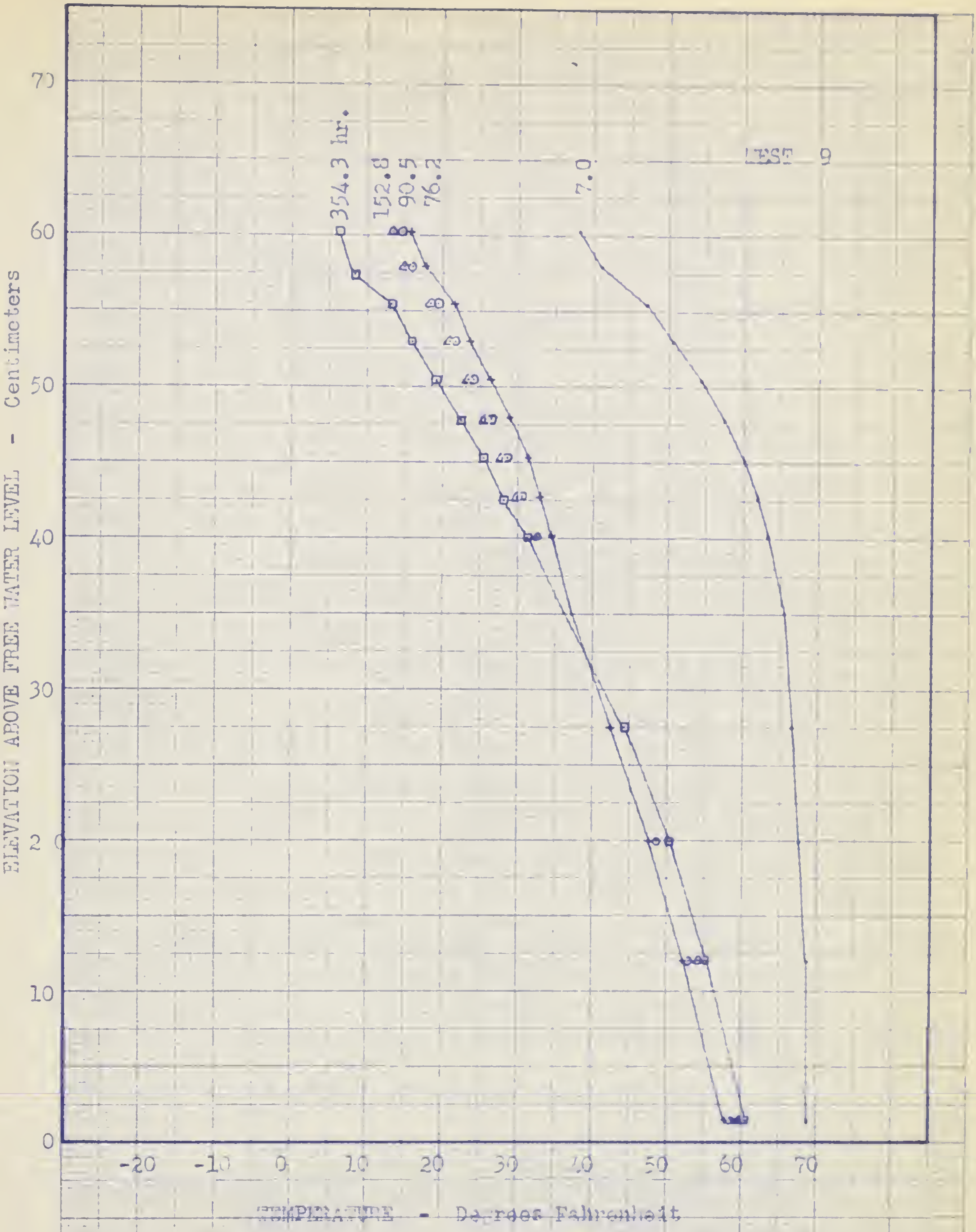


PLATE 22 A

TEMPERATURE PROFILES

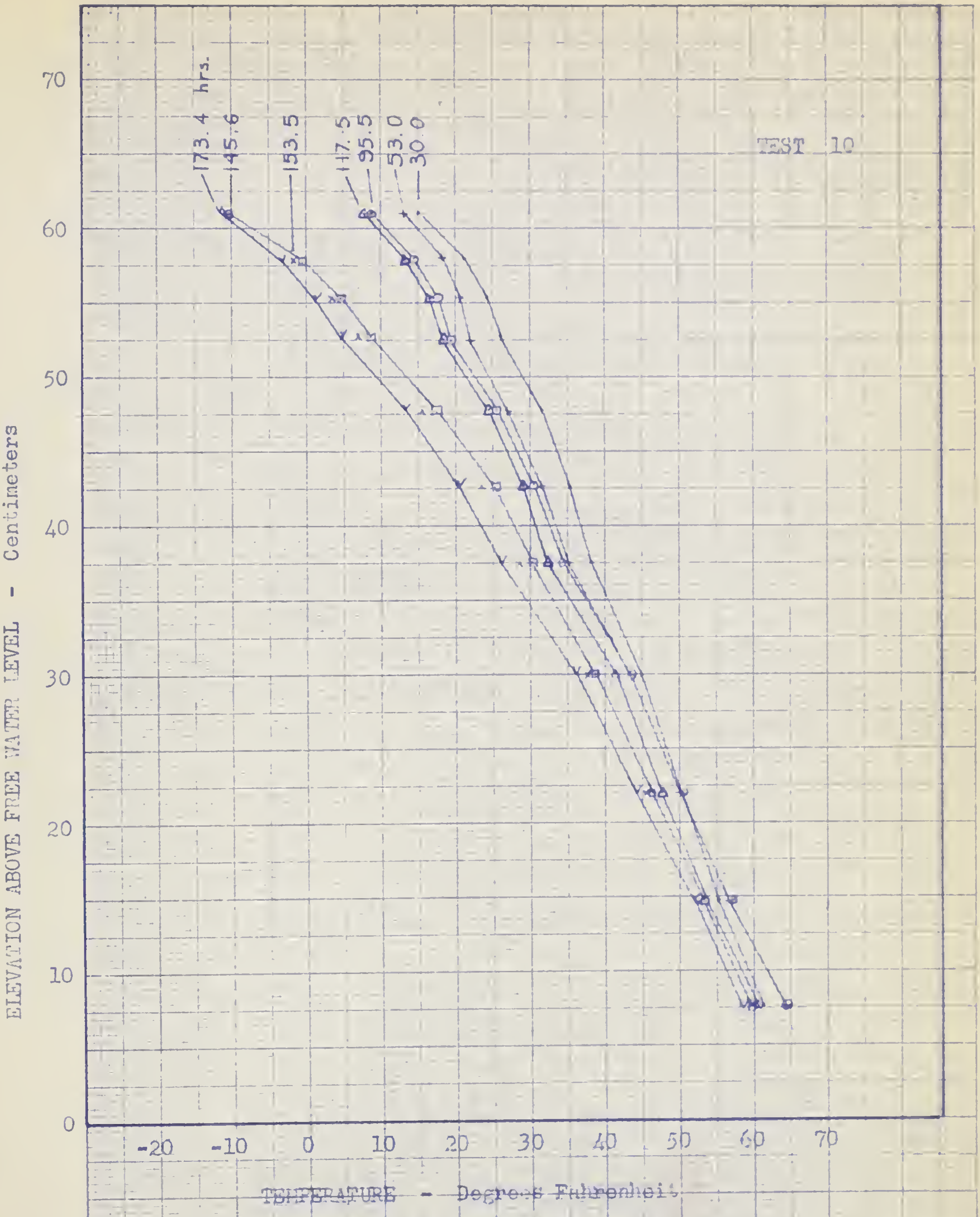


PLATE 22 B

TEMPERATURE PROFILES

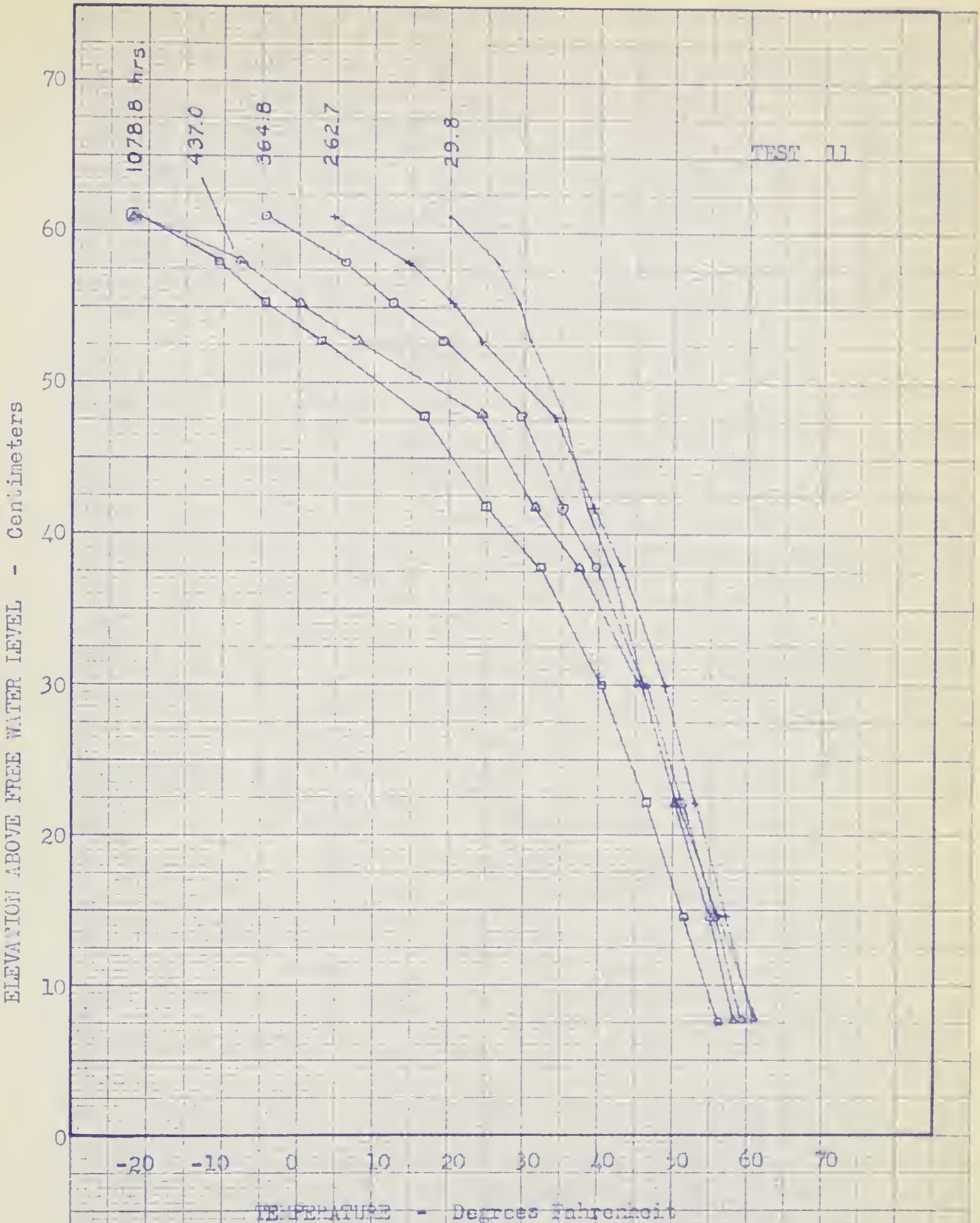


PLATE 22C

TEMPERATURE PROFILES

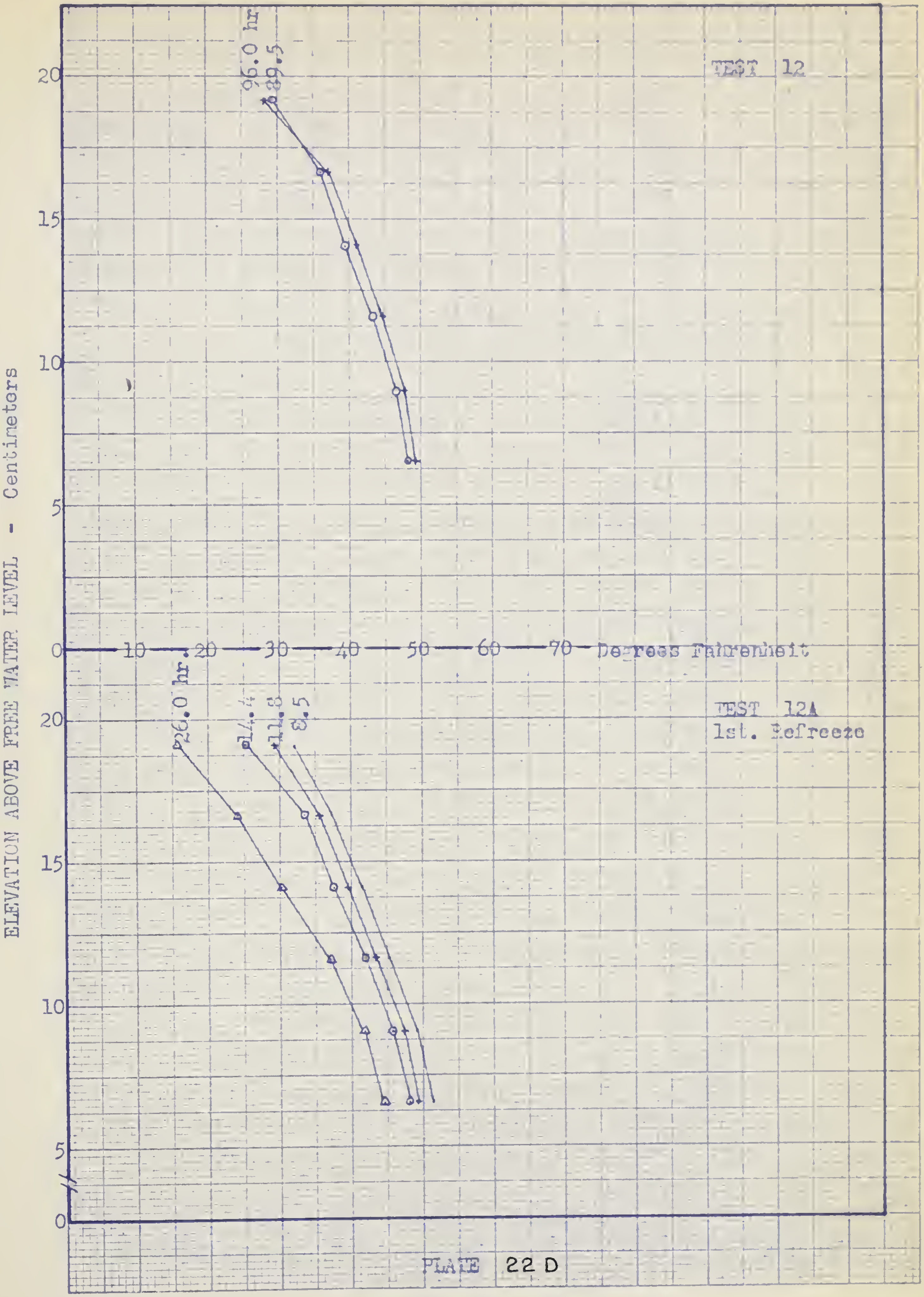


PLATE 22 D

TEMPERATURE PROFILES

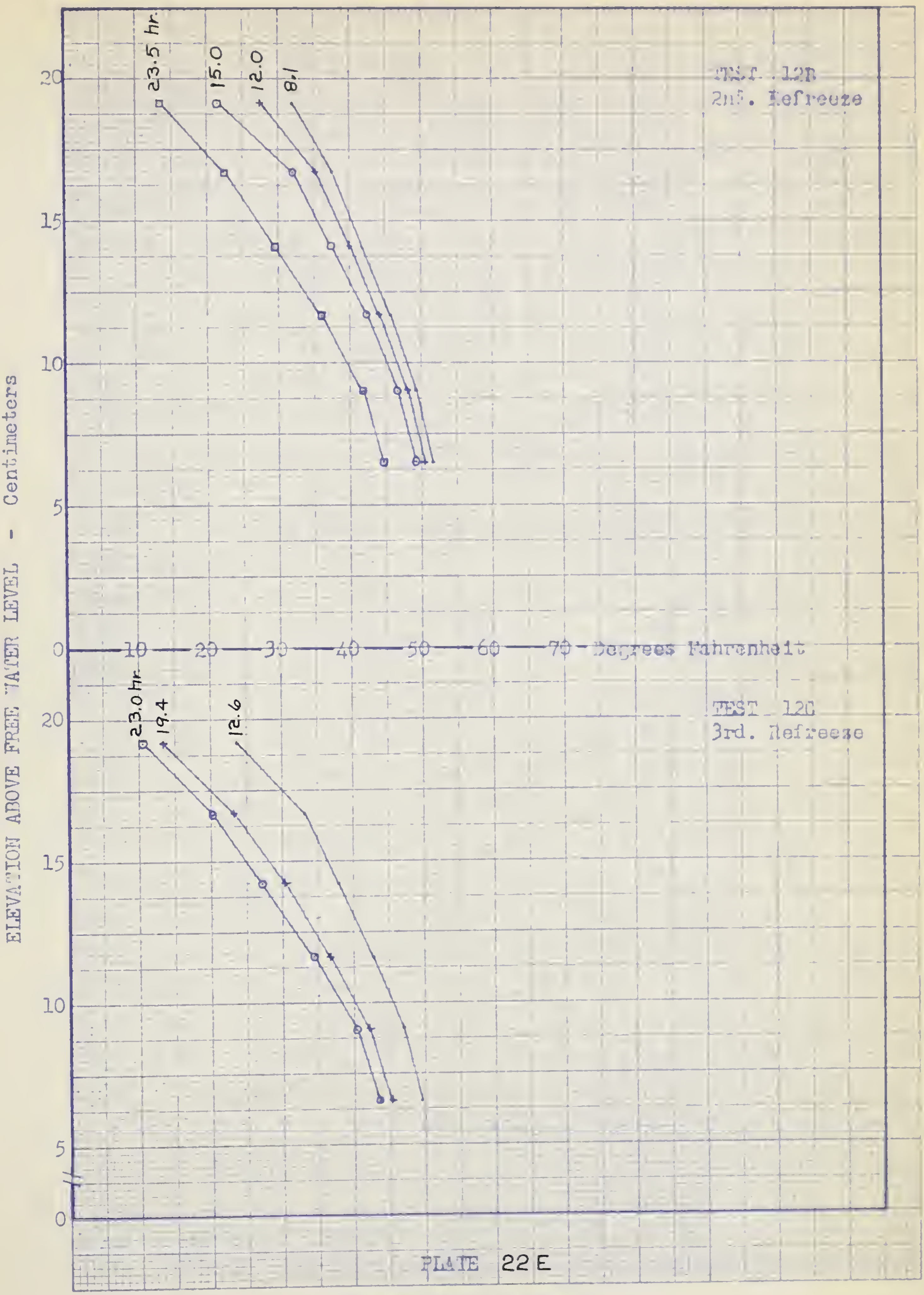


PLATE 22 E

TEMPERATURE PROFILES

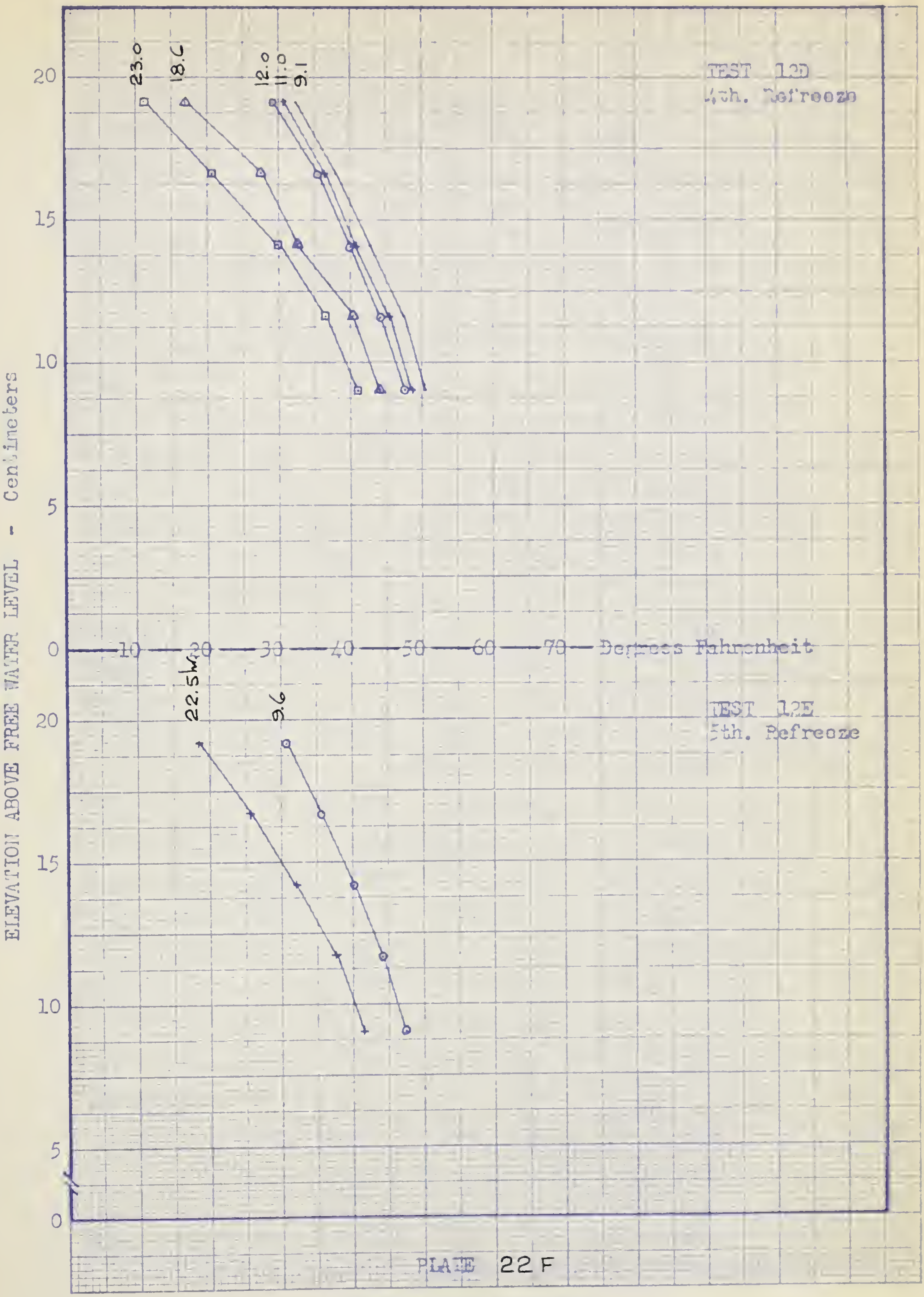


PLATE 22 F

TEMPERATURE PROFILES

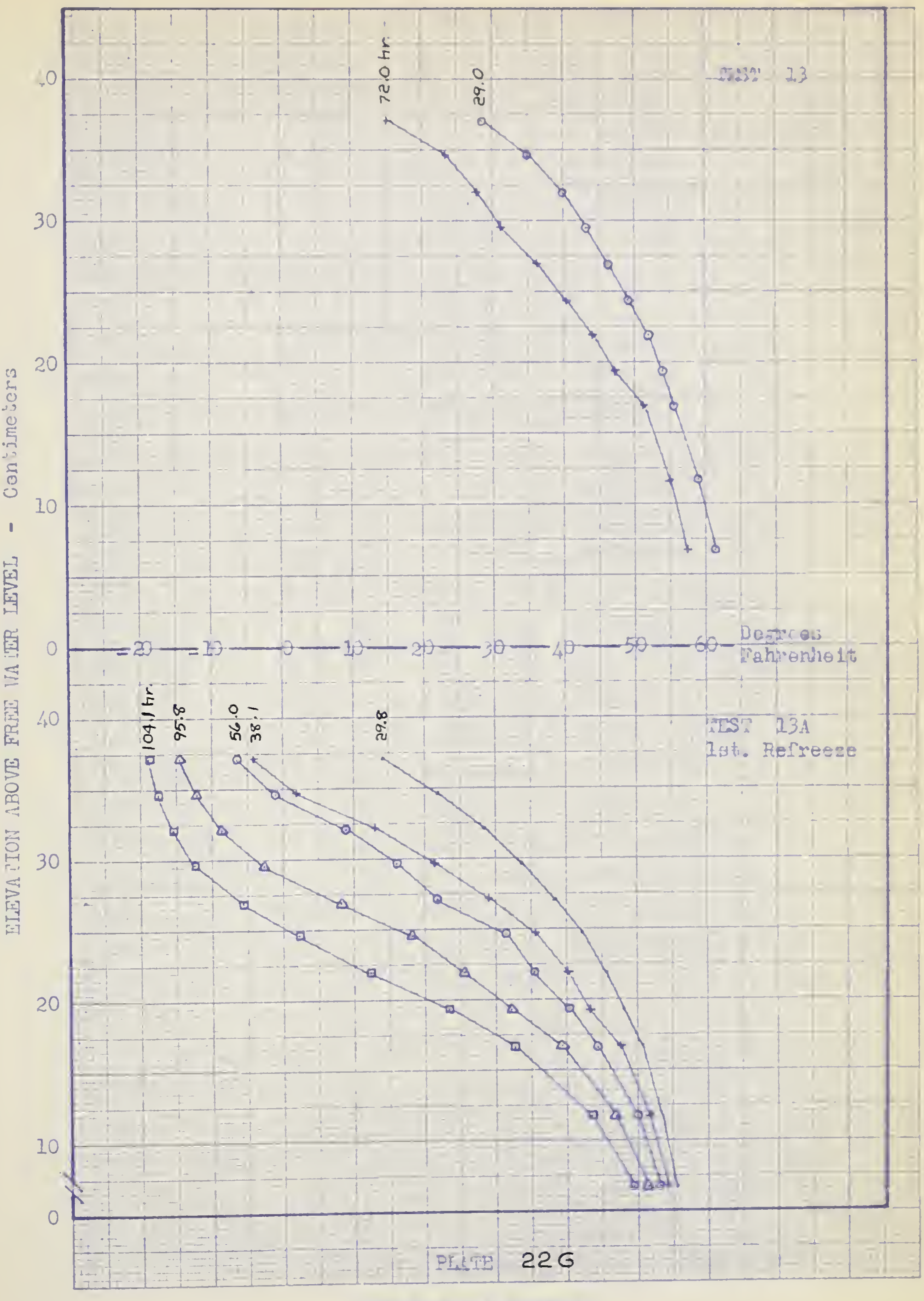


PLATE 22 G

TEMPERATURE PROFILES

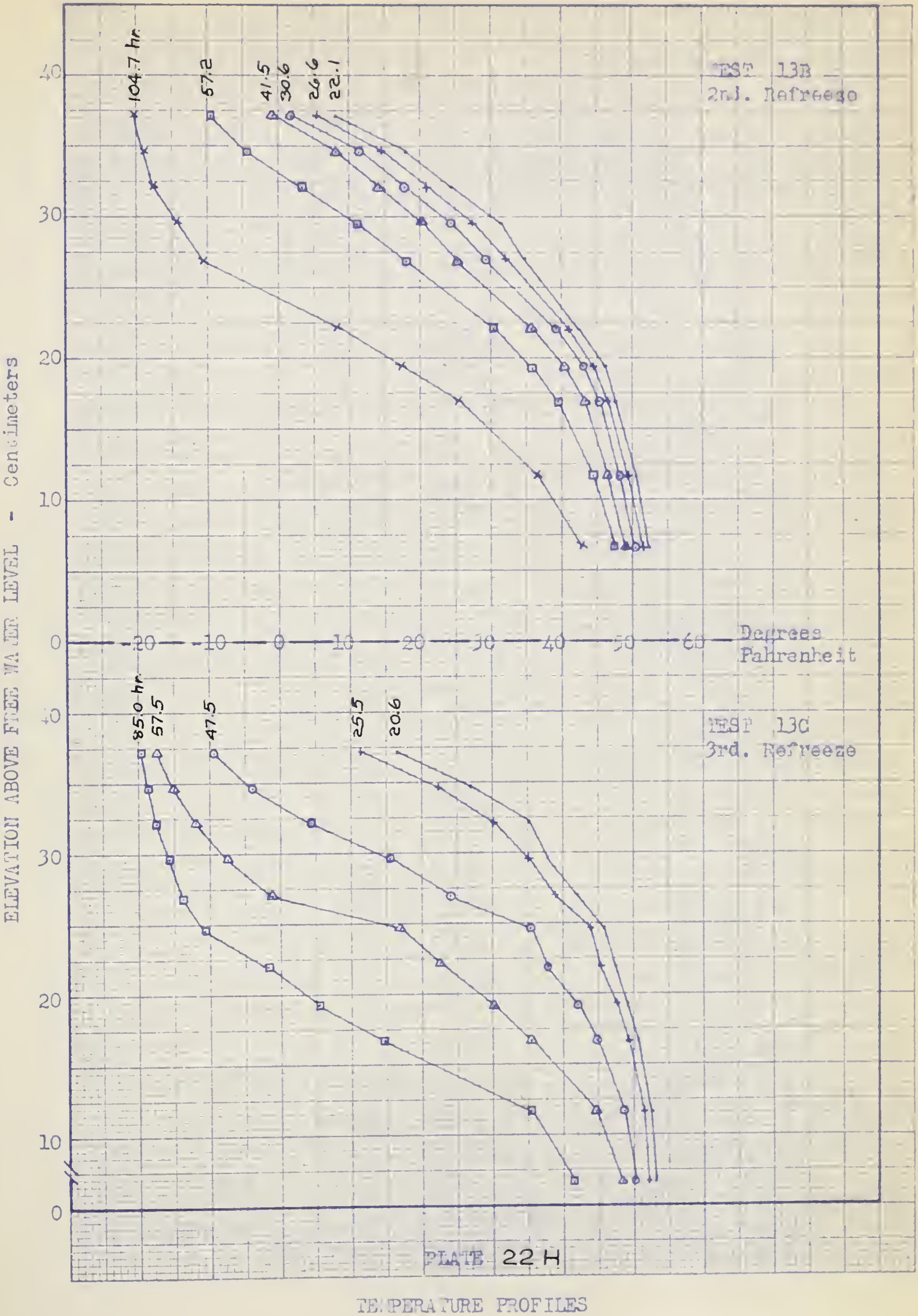


PLATE 22 H

TEMPERATURE PROFILES

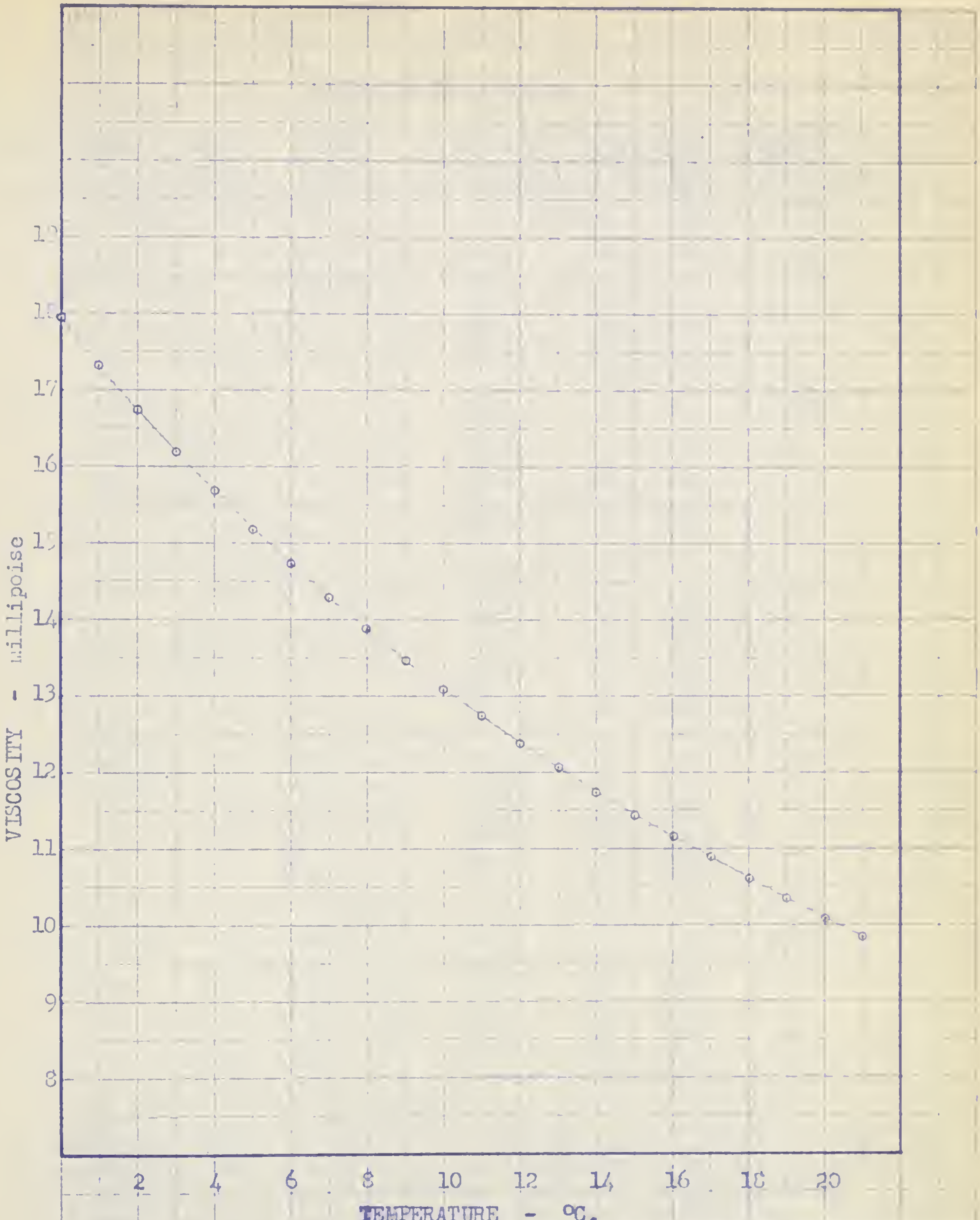


PLATE 23

VISCOSITY OF WATER

TABLE V

VISCOSITY CORRECTIONS

TEST	TIME Hr.	ELEV. Cm.	TEMP. °F	TEMP. °C	VISCOSITY Millipoise	TOTAL HEAD Cm. of H_2O		ELEV. OF FROST LINE-Cm.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
9	76.2	0	60.0	15.5	11.3	0	0	42.9
"	"	12.7	50.5	10.3	13.0	1	1	"
"	"	17.7	47.5	8.6	13.6	1	1	"
"	"	22.6	44.5	7.0	14.3	21	15	"
"	"	26.6	41.5	5.3	15.0	27	19	"
10	173.4	0	63.5	17.5	10.8	0	0	32.3
"	"	13.3	52.5	11.2	12.6	24	21	"
"	"	17.9	47.5	8.6	13.6	51	42	"
"	"	22.5	42.5	5.8	14.8	103	78	"
"	"	27.3	38.0	3.3	16.0	178	127	"
"	"	33.1	31.0	-0.6	17.9	310	206	"
11	437.0	0	60.5	15.8	11.2	0	0	40.9
"	"	13.3	54.5	12.5	12.2	16	14	"
"	"	17.9	52.0	11.1	13.7	11	10	"
"	"	22.5	49.0	9.4	13.3	40	33	"
"	"	27.3	46.5	8.1	13.8	93	72	"
"	"	33.1	41.0	5.0	15.2	138	103	"
12B	23.5	0	47.5	8.6	13.6	0	0	12.9
"	"	2.6	47.0	8.3	13.7	9	7	"
"	"	5.1	45.0	7.2	14.2	35	26	"
"	"	7.5	42.5	5.8	14.8	119	109	"
"	"	10.0	38.5	3.6	15.9	145	126	"
"	"	12.5	32.5	0.3	17.7	379	266	"
13B	57.2	0	49.5	9.7	13.2	0	0	20.8
"	"	2.6	48.5	9.2	13.4	7	5	"
"	"	5.1	47.5	8.6	13.6	25	18	"
"	"	7.5	46.0	7.8	13.9	86	63	"
"	"	10.0	44.5	7.0	14.3	198	144	"
"	"	12.5	42.5	5.8	14.8	379	269	"

NOTE: The total head values in column (7) were taken directly from Tables III(A) to III(E). The differences between values vertically adjacent in this column were corrected in accordance with equation (II.16), using the viscosity of water at 20°C as standard. Starting with a total head value of zero at the reservoir, the corrected differences were added accumulatively, to get the viscosity corrected total head values listed in column (8). The average of consecutive values in column (6) was used as the average viscosity for the corresponding interval along the specimen.

[illegible]

[illegible]

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TABLE VI

DETERMINATION OF SURCHARGE

Weight of top plate	148 gm.
Thrust of Ames dial shaft	250 gm.
Total	398 gm.
Diameter of sample	3.12" = 7.94 cm.
Cross-section area	49.4 $cm.^2$
Fixed surcharge	8.1 $gm./cm.^2$
Depth of lucite rings	1.00" = 2.54 cm.
Weight of lucite rings	37.5 gm.
Weight of lucite rings per cm. of length	14.8 gm.
Weight of soil per cm. length of sample[1]	93.9 gm.
Combined weight per cm. of length	109 gm.
Combined unit weight	2.21 $gm./cm.^2$
Total surcharge	(8 = 2.21 x length in cm.) $gm./cm.^2$

[1] Based on a unit weight determined using assumed values for the void ratio and the degree of saturation. The maximum error due to these assumptions is ± 5%.

TABLE VII

SURCHARGE AT TAPPING POINTS

TEST	MANOMETER 1	2	3	4	5
9		95	116	86	106
10	73	107	116	85	96
11	73	107	116	85	96
12-12F	48	42	37	31	26
13-13C	87	81	76	71	65

TABLE VIII

VOID RATIO CORRECTIONS

TEST	TIME Hr.	ELEV. Cm.	EFFECTIVE PRESSURE Kg./Cm.^{2}	VOID RATIO e	$\frac{e^3}{1+e}$	TOTAL HEAD Cm. of H_2O	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
9	76.2	0	0.15	0.595	0.132	0	0
"	"	12.7	0.13	0.598	0.134	1	1
"	"	17.7	0.13	0.598	0.134	1	1
"	"	22.6	0.14	0.596	0.133	15	15
"	"	26.6	0.14	0.596	0.133	10	19
10	173.4	0	0.15	0.595	0.132	0	0
"	"	13.3	0.15	0.595	0.132	21	21
"	"	17.9	0.18	0.590	0.130	42	42
"	"	22.5	0.22	0.584	0.126	78	77
"	"	27.3	0.29	0.576	0.122	127	123
"	"	33.1	0.42	0.565	0.115	206	194
11	437.0	0	0.15	0.595	0.132	0	0
"	"	13.3	0.14	0.596	0.133	14	14
"	"	17.9	0.14	0.596	0.133	10	10
"	"	22.5	0.16	0.593	0.131	33	33
"	"	27.3	0.21	0.585	0.126	72	70
"	"	33.1	0.24	0.581	0.124	103	99
12B	23.5	0	0.06	0.611	0.141	0	0
"	"	2.6	0.06	0.611	0.141	7	7
"	"	5.1	0.08	0.608	0.140	26	26
"	"	7.5	0.16	0.593	0.131	109	105
"	"	10.0	0.19	0.588	0.128	126	120
"	"	12.5	0.42	0.565	0.115	266	241
13B	57.2	0	0.10	0.604	0.137	0	0
"	"	2.6	0.10	0.604	0.137	5	5
"	"	5.1	0.11	0.602	0.136	18	18
"	"	7.5	0.17	0.592	0.131	63	62
"	"	10.0	0.28	0.577	0.122	144	137
"	"	12.5	0.46	0.562	0.114	269	244

NOTE: In each test, the void ratio at the reservoir was taken as standard for correction purposes. Column (7) consists of viscosity corrected total head values from Table IV. Differences in consecutive values were corrected for void ratio on the basis of equation (V.18). Starting with zero at the reservoir, the corrected differences were added, accumulatively, to get the total head values listed in Column (8). These are corrected for both viscosity and void ratio differences.

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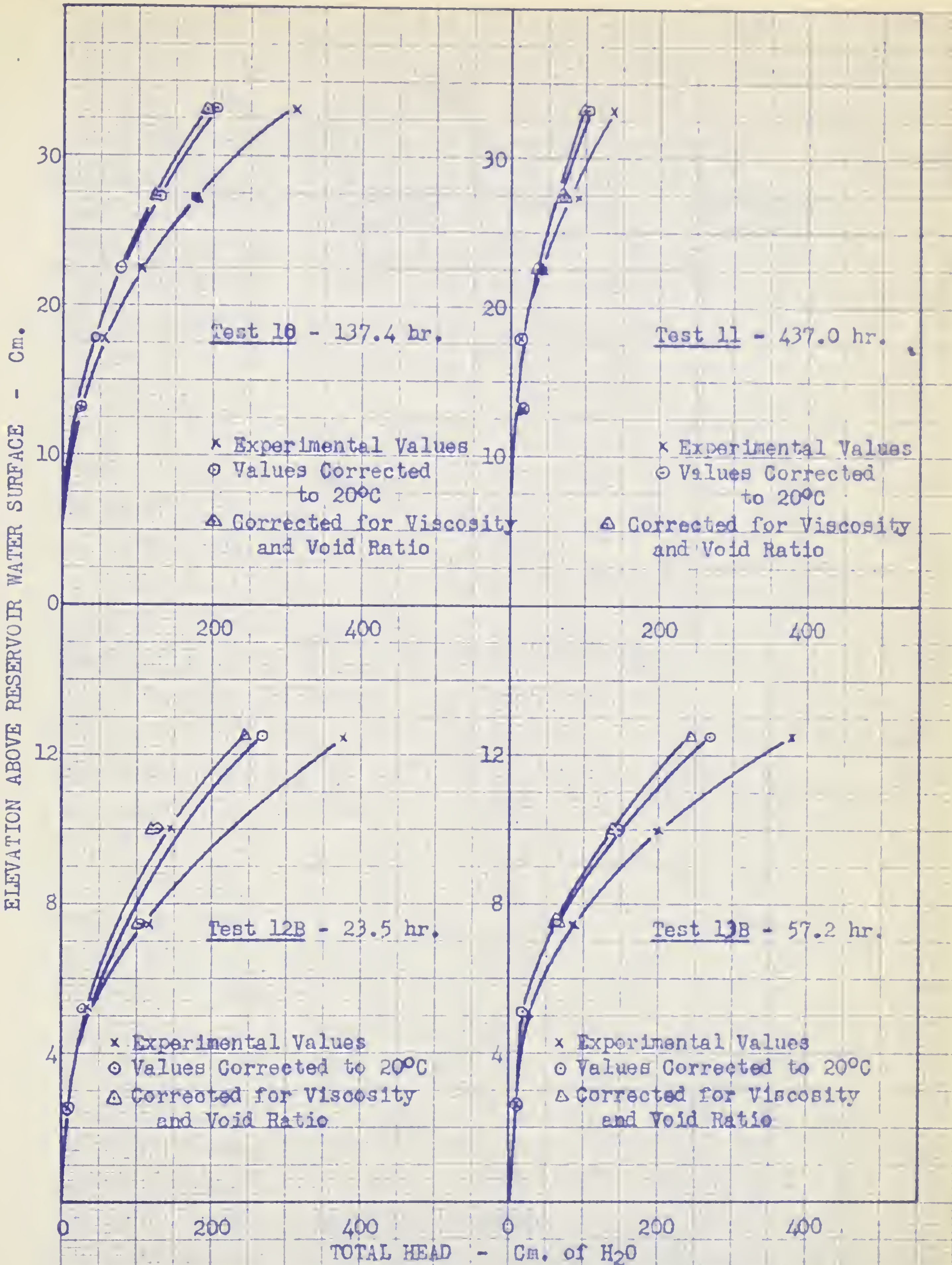


PLATE 24

A COMPARISON OF TOTAL HEAD VALUES
WITH AND WITHOUT CORRECTIONS

TABLE IX

HYDRAULIC GRADIENT AND PERMEABILITY COMPUTATIONS

ELEV.	TOTAL HEAD Cm. of H_2O		HYDRAULIC GRADIENT		PERMEABILITY Cm./Sec. x 10^8		PIEZOMETRIC PRESSURE Cm. of H_2O	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Test 11 - 437.0 hr., Rate of heave = 0.0040 Cm./hr.								
0	0	0					0	0
			0.7	0.7	140	140		
13.3	9	9					22	22
			1.5	1.5	67	67		
17.9	16	16					34	34
			5.2	3.7	19	27		
22.5	40	33					62	56
			8.3	6.0	12	17		
27.3	80	62					107	89
			10	6.4	10	16		
33.1	138	99					171	132
Test 12A - 23.5 hr., Rate of heave = 0.044 Cm./hr.								
0	0	0					0	0
			3.5	2.7	310	410		
2.6	9	7					12	10
			10	7.6	110	150		
5.1	35	26					40	31
			28	20	39	55		
7.5	102	75					110	83
			49	27	22	41		
10.0	225	143					235	153
			62	39	18	28		
12.5	379	241					392	254
Test 13B - 57.2 hr., Rate of heave = 0.022 Cm./hr.								
0	0	0					0	0
			2.7	1.9	210	290		
2.6	7	5					10	8
			7.2	5.2	78	110		
5.1	25	18					30	23
			26	18	22	31		
7.5	86	62					94	70
			45	30	12	19		
10.0	198	137					208	147
			72	43	7.8	13		
12.5	379	244					292	257

NOTE: In the pairs of columns (2)-(3), (4)-(5), (6)-(7) and (8)-(9), the values in the second column of each pair contain void ratio and viscosity corrections, while those in the first column do not.

[illegible]

[illegible]

[illegible]

[illegible]

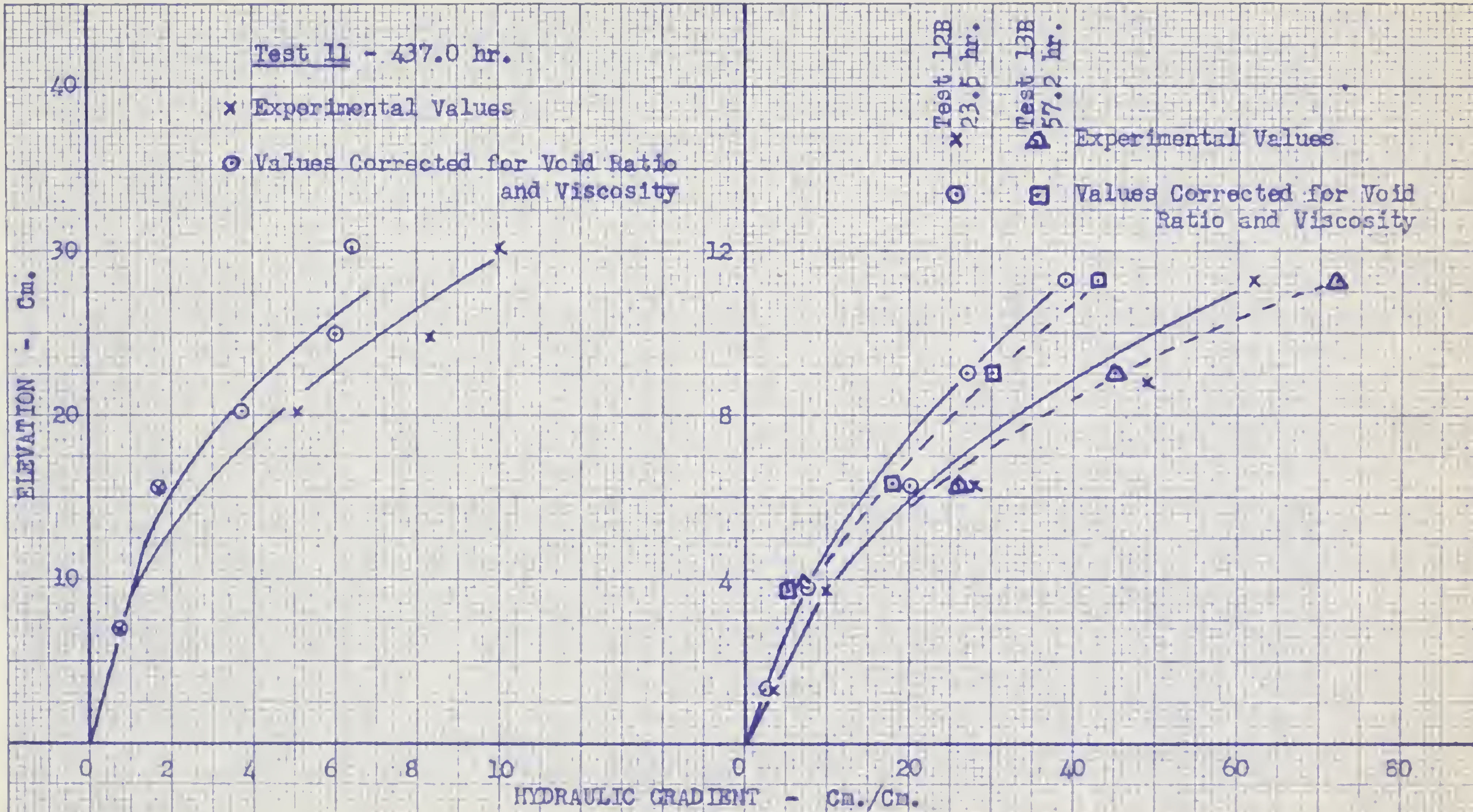


PLATE 25

HYDRAULIC GRADIENT PROFILES

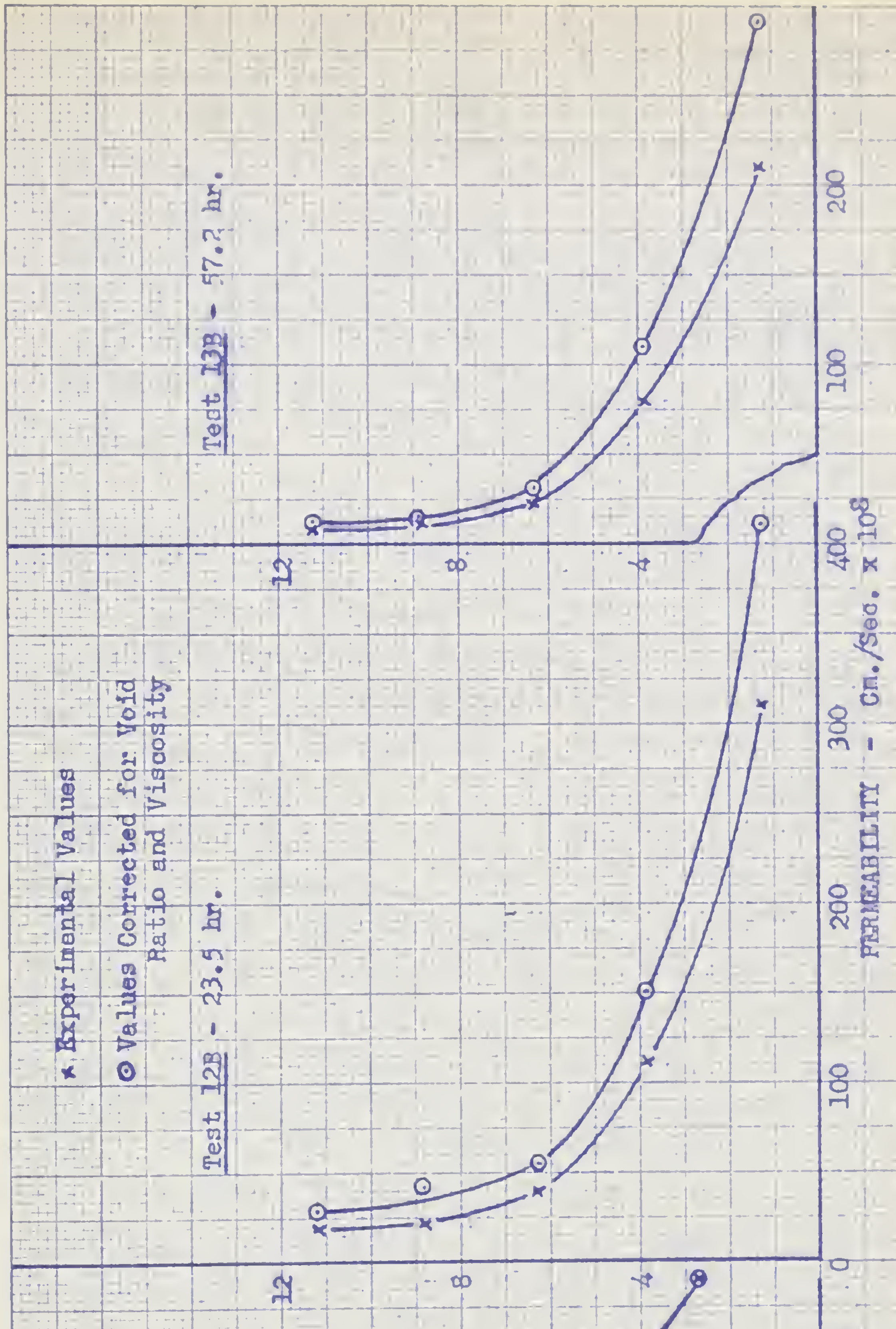


PLATE 26

PERMEABILITY PROFILES

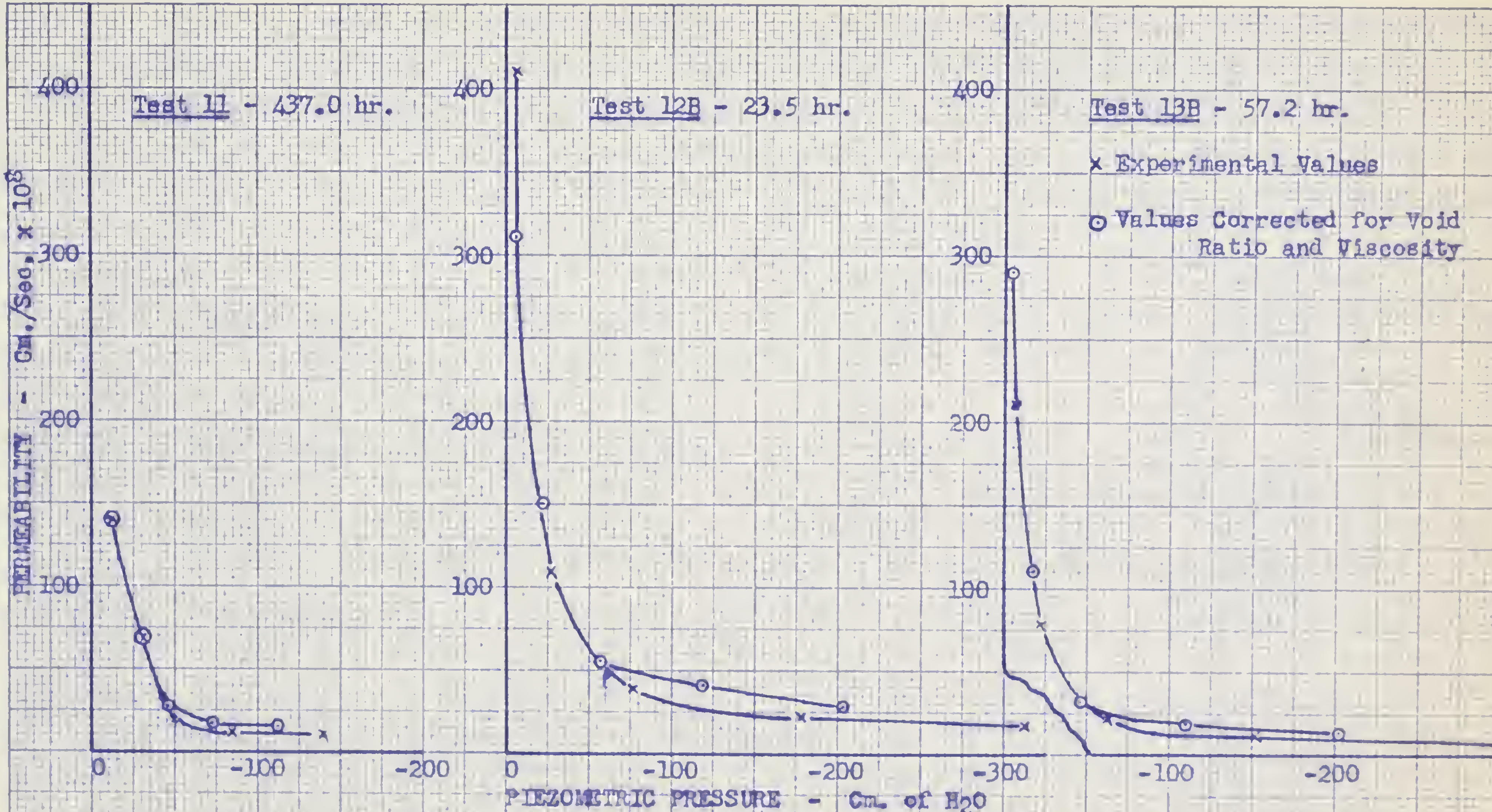


PLATE 27

PERMEABILITY AS A FUNCTION OF THE PRESSURE IN THE PORE WATER

TABLE X

COMPUTATION OF PERMEABILITY AT VARIOUS TIMES IN TEST 13B

	ELEV. Cm.	PIEZOMETRIC PRESSURE Cm. of H_2O	TOTAL HEAD Cm. of H_2O	HEAD LOSS Cm. of H_2O	i	PERMEABILITY Cm./Sec.
	(1)	(2)	(3)	(4)	(5)	(6)
	0	0	0			
				2	0.8	2.1×10^{-5}
Time - 22.1 Hr.	2.6	5	2			
				3	1	1.7×10^{-5}
Rate of Heave	5.1	10	5			
0.061 Cm./Hr.				7	3	5.6×10^{-6}
	7.5	20	12			
				26	10	1.7×10^{-6}
	10.0	48	38			
				43	17	1.0×10^{-6}
	12.5	94	81			
	0	0	0			
				5	2	6.4×10^{-6}
Time - 26.6 Hr.	2.6	8	5			
				8	3	4.2×10^{-6}
Rate of Heave	5.1	18	13			
0.046 Cm./Hr.				21	9	1.4×10^{-6}
	7.5	42	34			
				54	22	5.8×10^{-7}
	10.0	98	88			
				69	28	4.4×10^{-7}
	12.5	170	157			
	0	0	0			
				8	3	3.1×10^{-6}
Time - 34.0 Hr.	2.6	11	8			
				15	6	1.5×10^{-6}
Rate of Heave	5.1	28	23			
0.033 Cm./Hr.				46	19	4.7×10^{-7}
	7.5	77	69			
				90	36	2.6×10^{-7}
	10.0	169	159			
				118	47	1.9×10^{-7}
	12.5	290	277			

TABLE X (Concluded)

	ELEV. Cm.	PIEZOMETRIC PRESSURE Cm. of H_2O	TOTAL HEAD Cm. of H_2O	HEAD LOSS Cm. of H_2O	i	PERMEABILITY Cm./Sec.
	(1)	(2)	(3)	(4)	(5)	(6)
	0	0	0			
				11	4	2.4×10^{-6}
Time - 110.0 Hr.	2.6	14	11			
				31	12	8.1×10^{-7}
Rate of Heave	5.1	47	42			
0.035 Cm./Hr.				136	57	1.7×10^{-7}
	7.5	186	178			
				192	77	1.2×10^{-7}
	10.0	380	370			
				258	103	9.4×10^{-8}
	12.5	641	628			

NOTE: The rate of heave was computed from the heave curve on Plate 20E. The total head values listed have not been corrected for temperature or void ratio variations. All the piezometric pressure and total head values are negative.

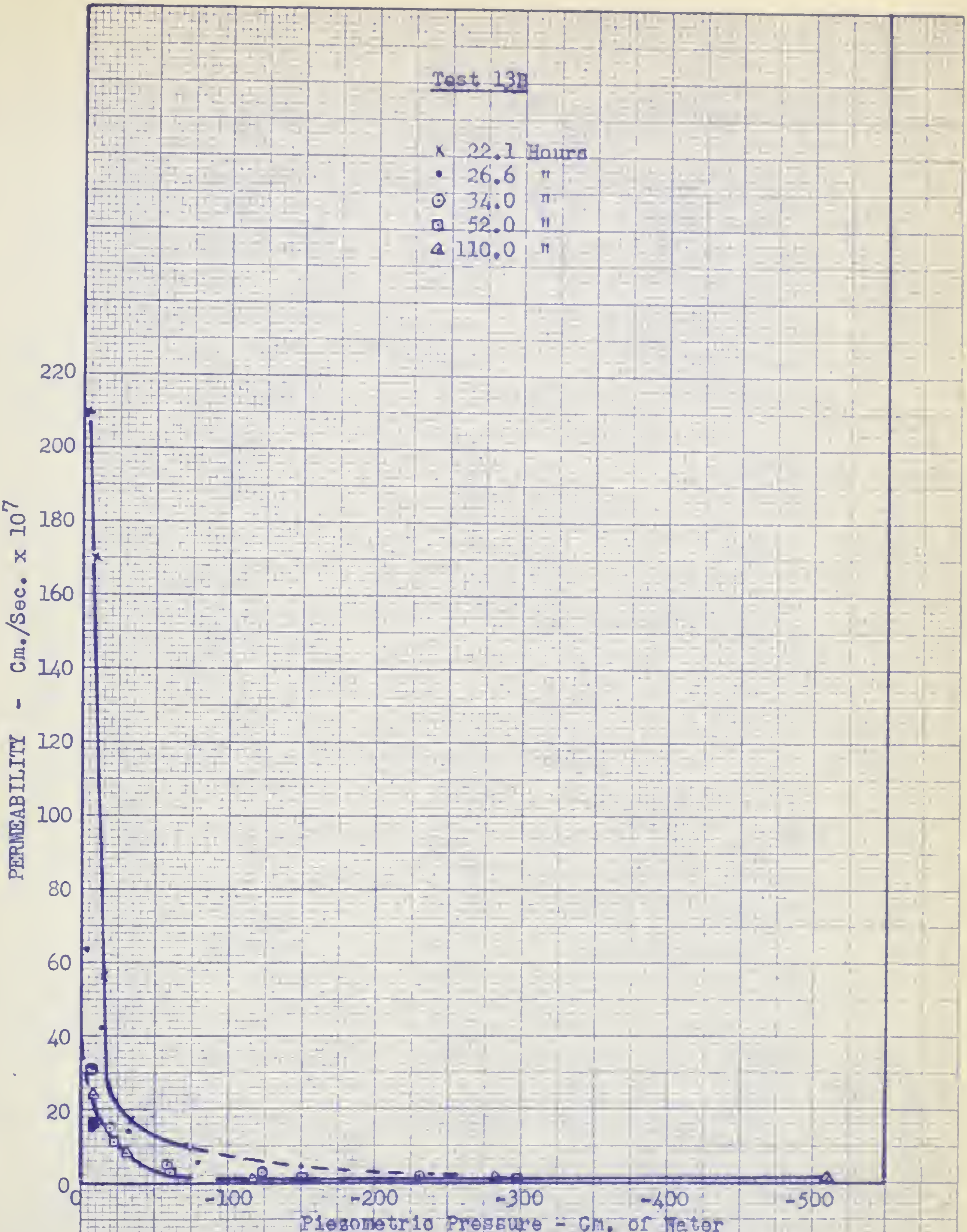


PLATE 28

PERMEABILITY AS A FUNCTION OF PRESSURE AT VARIOUS TIMES IN THE SAME TEST

TABLE XI

HYDRAULIC GRADIENT VALUES AT DIFFERENT TIMES AND ELEVATIONS
TEST 10.

ELEV. Cm.	TOTAL HEAD Cm.	i	ELEV. Cm.	TOTAL HEAD Cm.	i
(1)	(2)	(3)	(1)	(2)	(3)
Time - 30.0 hr.			Time - 145.6 hr.		
0	0		0	0	
		+0.3			0.0
13.3	+4		13.3	0	
		+1			-1
17.9	+9		17.9	-5	
		+1			-2.4
22.5	+12		22.5	-16	
		0			-7.5
27.3	+13		27.3	-42	
		+1			-14
33.1	+19		33.1	-124	
Time - 95.5 hr.			Time - 153.5 hr.		
0	0		0	0	
		+0.4			-0.2
13.3	+5		13.3	-3	
		+1			-1
17.9	+8		17.9	-8	
		-1			-4.8
22.5	+4		22.5	-29	
		-2			-9.8
27.3	-5		27.3	-76	
		-4.3			-20
33.1	-30		33.1	-194	
Time - 117.5 hr.			Time - 158.0 hr.		
0	0		0	0	
		+0.4			-0.5
13.3	+5		13.3	-6	
		0.0			-2
17.9	+4		17.9	-15	
		-1			-6.4
22.5	-1		22.5	-44	
		-4.4			-13
27.3	-22		27.3	-108	
		-7.2			-24
33.1	-64		33.1	-249	

NOTE: Hydraulic gradients tending to produce upward flow of water are shown as negative.

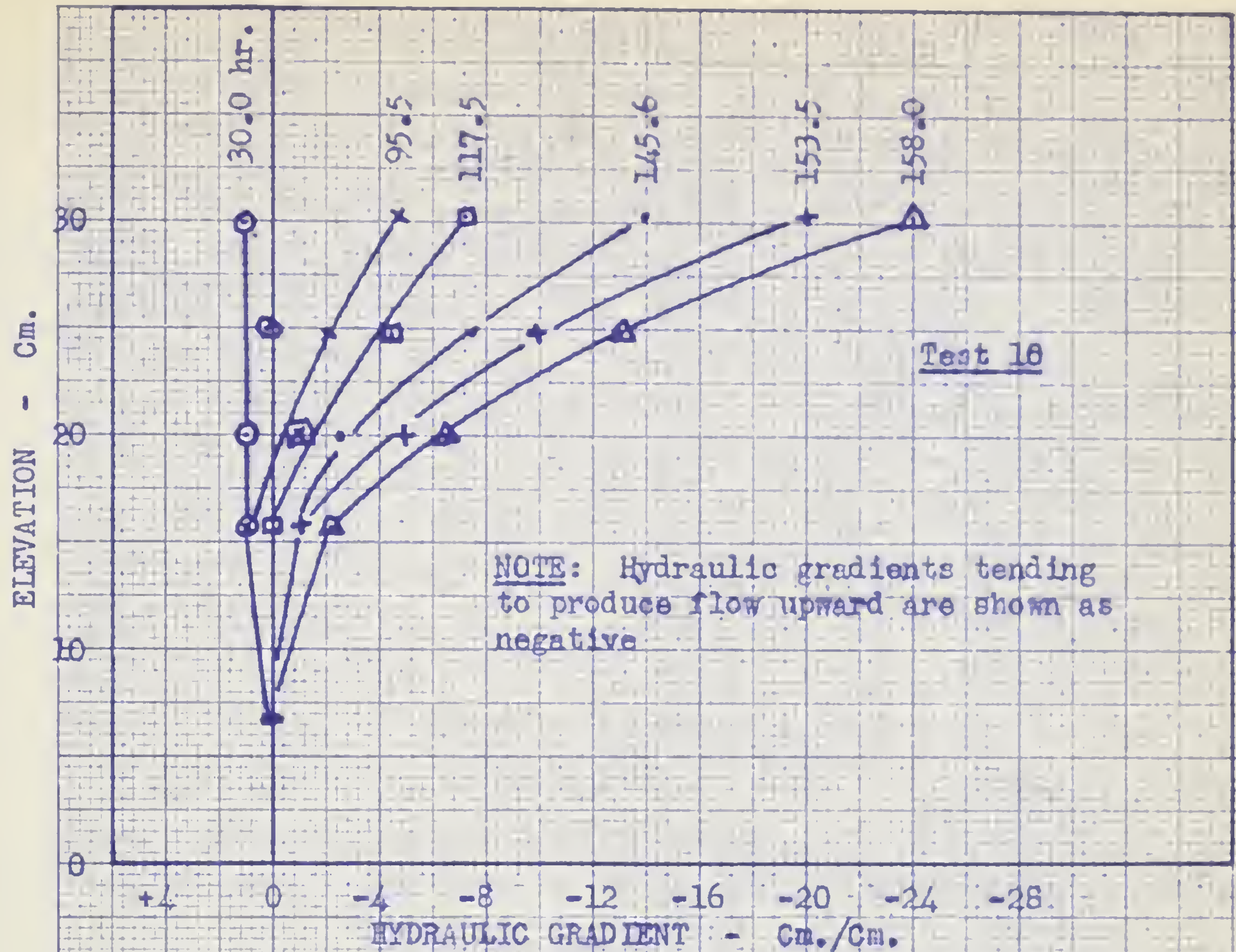


PLATE 29

HYDRAULIC GRADIENTS FOR DIFFERENT ELEVATIONS AND TIMES

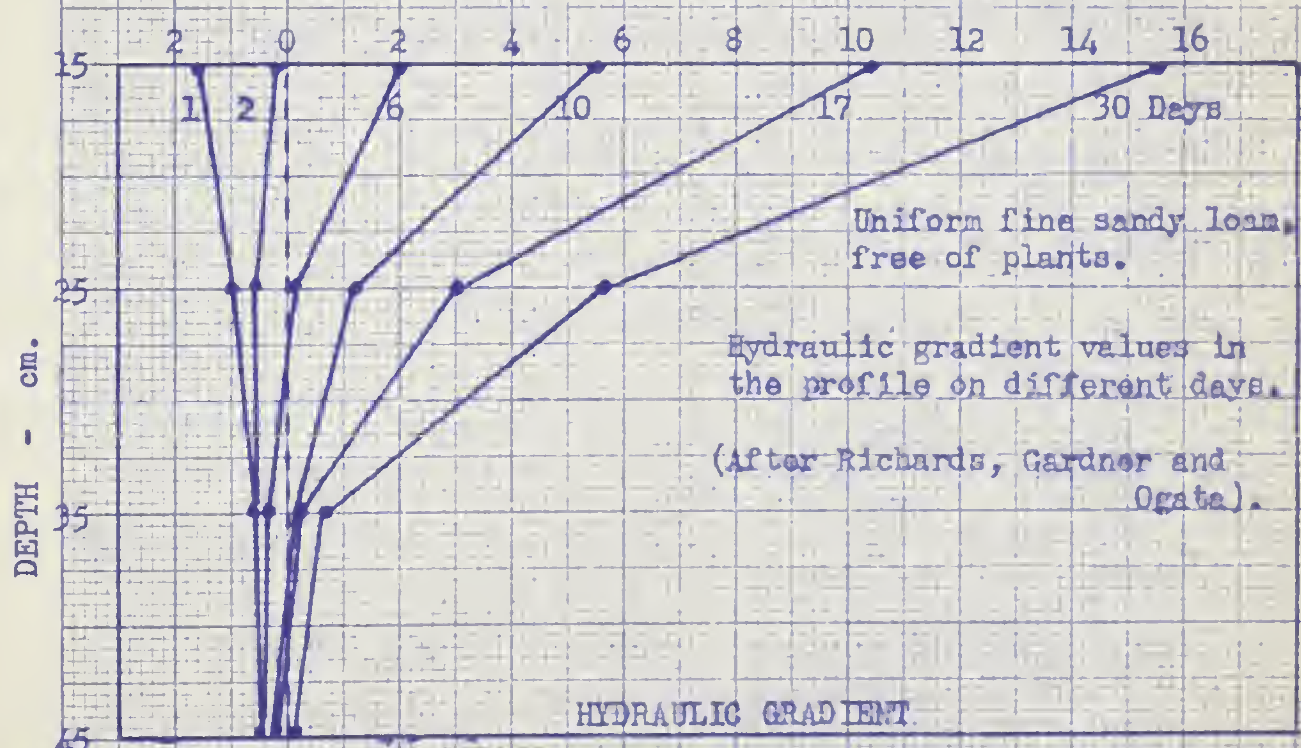
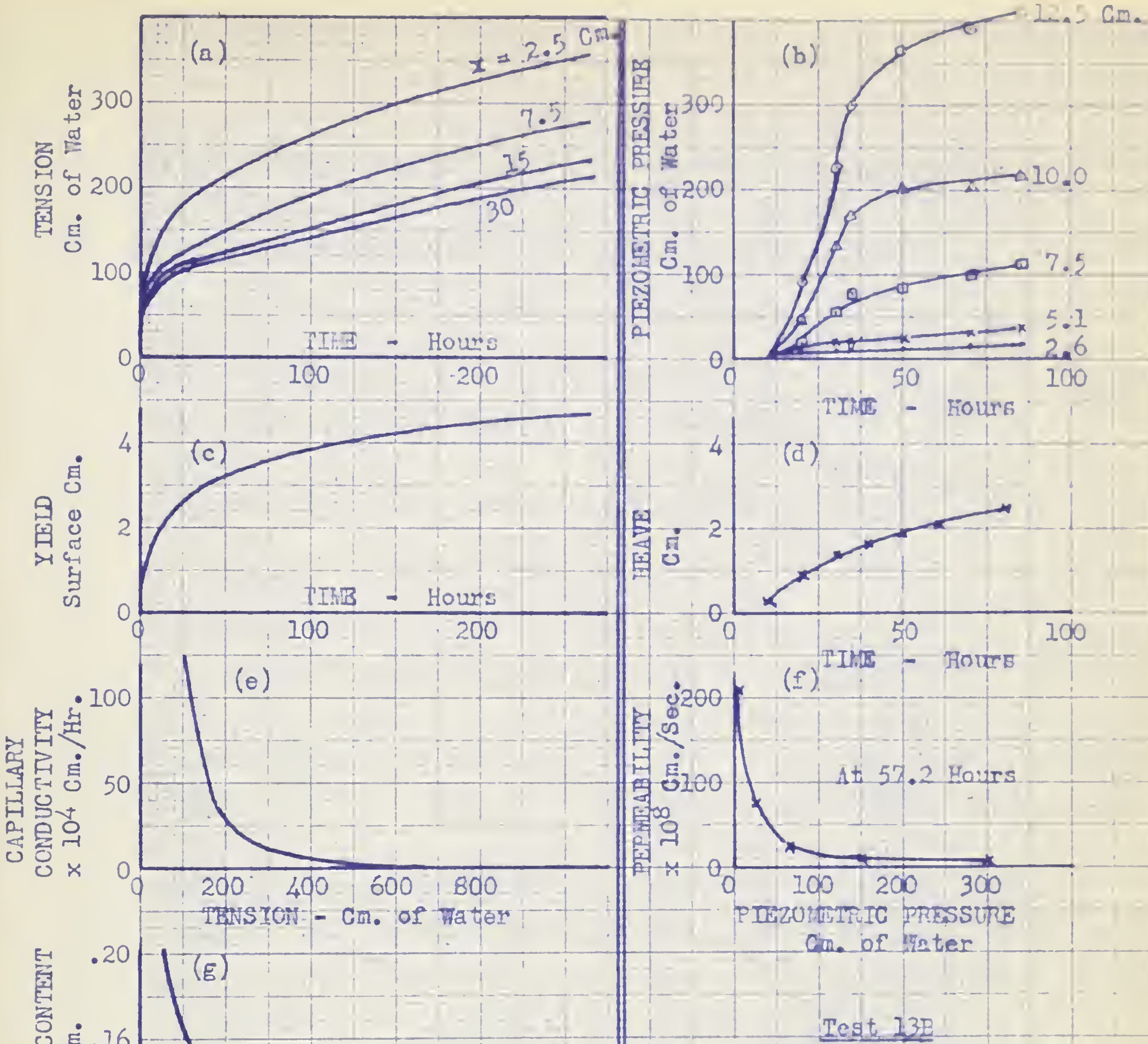
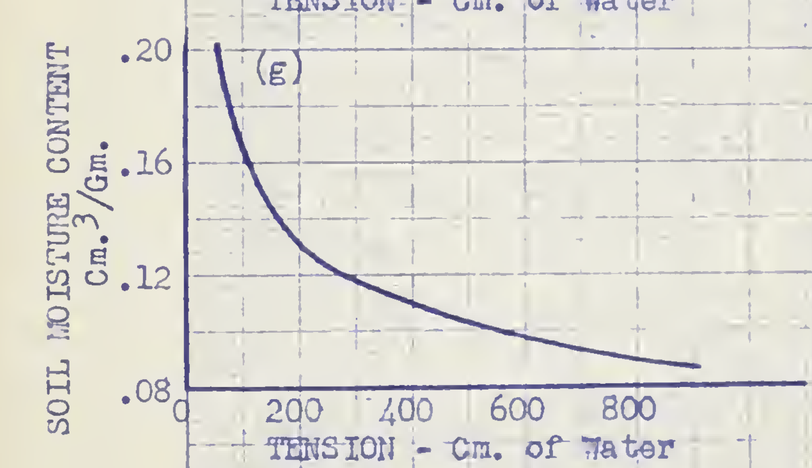


PLATE 30

HYDRAULIC GRADIENT AFTER TERMINATION OF IRRIGATION





(After Richards and Weeks)

NOTE:

1. The x values given in (a) refer to the distance of the point considered in the sample from the point of application of tension.

2. "Yield" is equivalent to superficial velocity.

3. Capillary conductivity is equivalent to permeability.

PLATE 31

A COMPARISON OF FROST HEAVE TEST RESULTS WITH PUBLISHED RESULTS OF TESTS USING APPLIED MOISTURE TENSIONS

TABLE XII

DETERMINATION OF CONSTANTS FOR FITTING CURVES TO EXPERIMENTAL DATA

Points selected from the experimental curve on Plate 32 (a)

1. $k_u = 3.1 \times 10^{-6}$ cm./sec. $h = 6$ cm.

2. $k_u = 5.0 \times 10^{-7}$ cm./sec. $h = 60$ cm.

3. $k_u = 1.7 \times 10^{-7}$ cm./sec. $h = 312$ cm.

Points selected from the experimental curve on Plate 33 (a)

1. $k_u = 2.9 \times 10^{-6}$ cm./sec. $h = 5$ cm.

2. $k_u = 3.7 \times 10^{-7}$ cm./sec. $h = 47$ cm.

3. $k_u = 9.4 \times 10^{-8}$ cm./sec. $h = 300$ cm.

TEST	TIME Hr.	POINTS USED	a	b	k_u Cm./Sec.
(1)	(2)	(3)	(4)	(5)	(6)
12B	23.5	1 - 3	56×10^{-6}	12	$56 \times 10^{-6}/(h + 12)$
12B	23.5	1 - 2	32×10^{-6}	4.2	$32 \times 10^{-6}/(h + 4.2)$
13B	57.2	4 - 6	28×10^{-6}	4.6	$28 \times 10^{-6}/(h + 4.6)$
13B	57.2	4 - 5	18×10^{-6}	1.2	$18 \times 10^{-6}/(h + 1.2)$
12B	23.5	1 - 3	18×10^{-3}	5700	$18 \times 10^{-3}/(h^2 + 5700)$
12B	23.5	1 - 2	21×10^{-4}	650	$21 \times 10^{-4}/(h^2 + 650)$
12B	23.5	1 - 2	0.13	41×10^3	$0.13/(h^3 + 41 \times 10^3)$
12B	23.5	1 - 2	7.7	2.5×10^6	$7.7/(h^4 + 2.5 \times 10^6)$
12B	23.5	1 - 3	27×10^{-7}	-1.6	$27 \times 10^{-7}/(h^{0.5} - 1.6)$
12B	23.5	1 - 2	32×10^{-7}	-1.4	$32 \times 10^{-7}/(h^{0.5} - 1.4)$

[illegible]

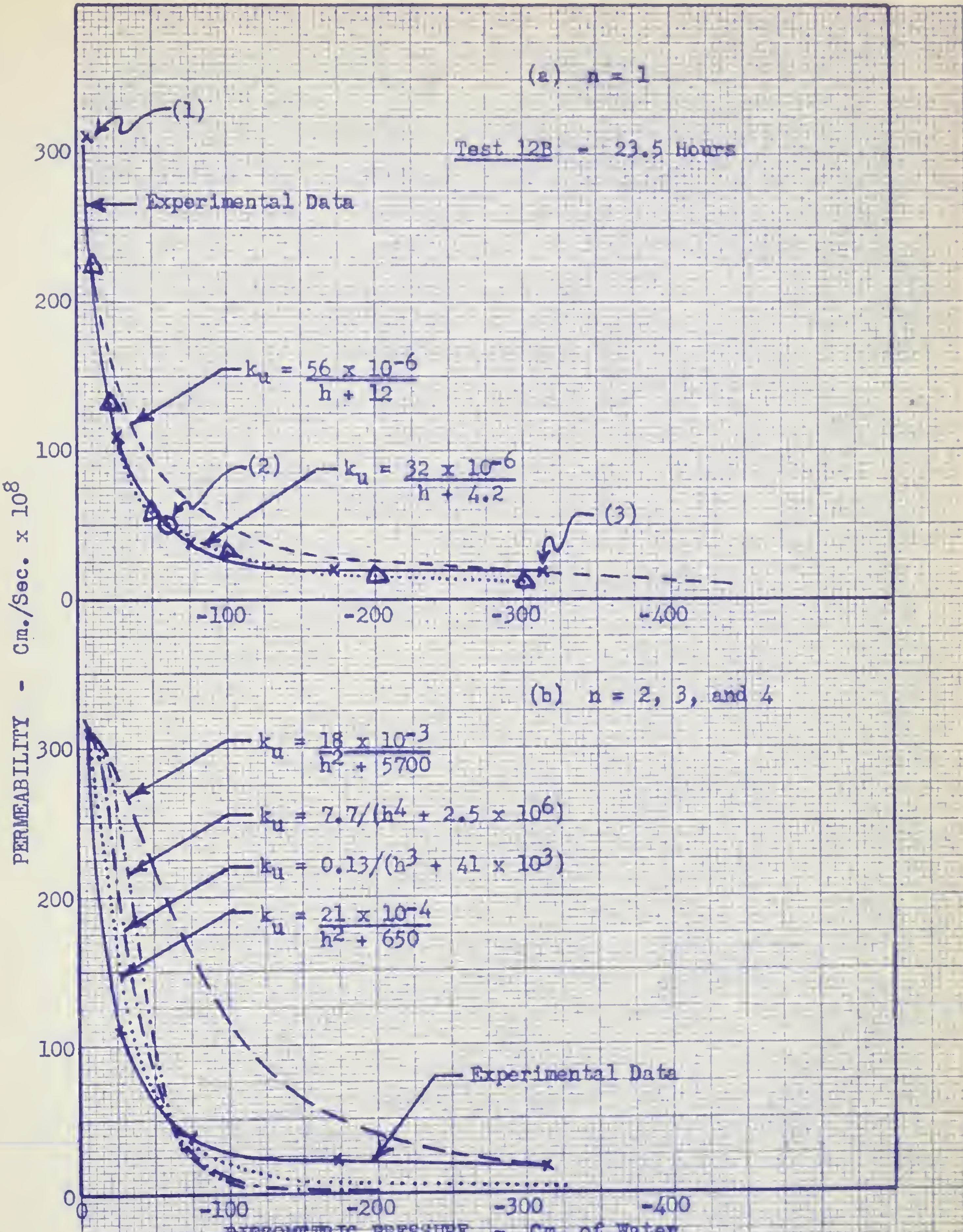


PLATE 32

FITTING CURVES TO PRESSURE-PERMEABILITY TEST DATA

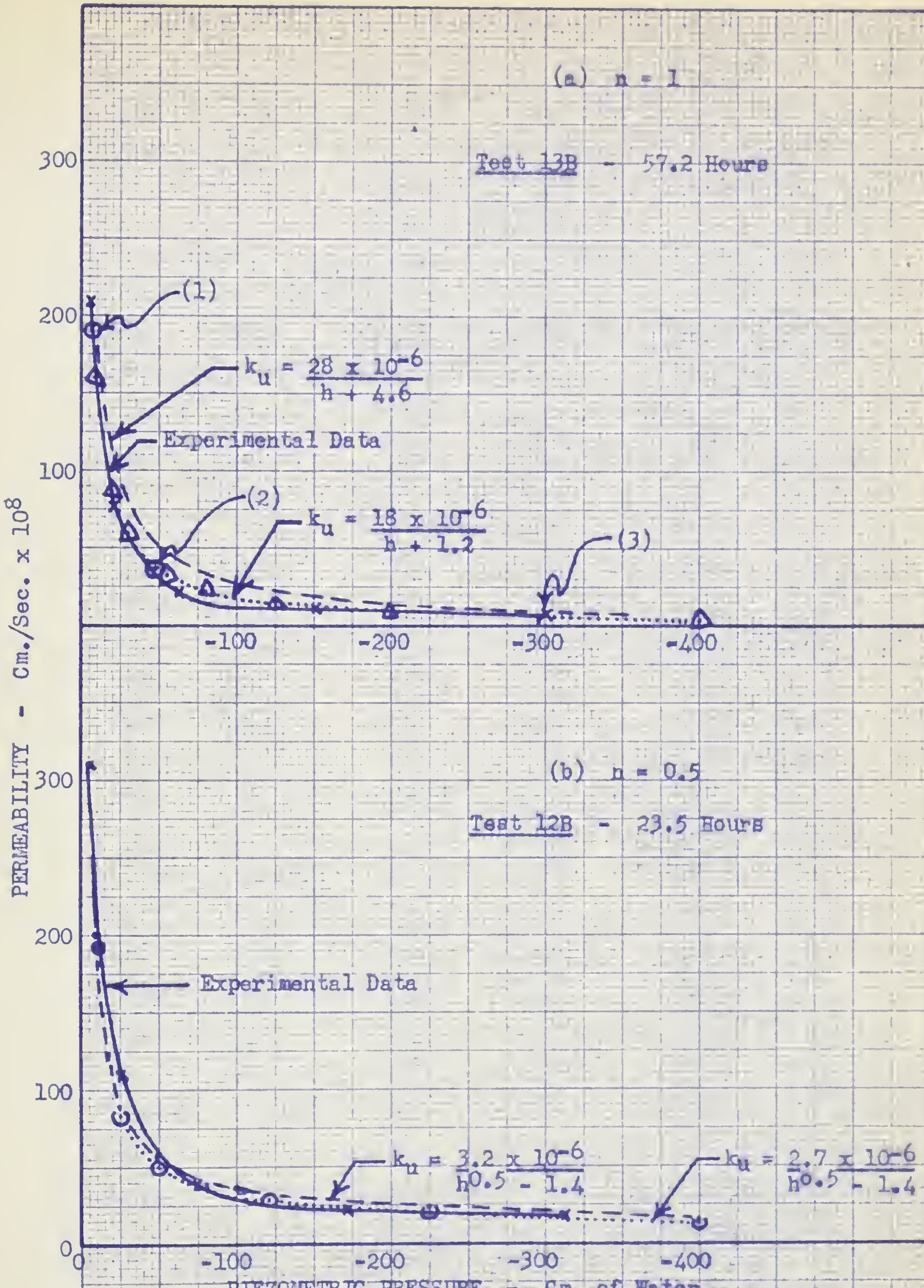


PLATE 33

FITTING CURVES TO PRESSURE-PERMEABILITY TEST DATA

TABLE XIII(A)

HEAVE VALUES FOR TEST 9.

TIME Hr.	HEAVE In.	TIME Hr.	HEAVE In.	TIME Hr.	HEAVE In.
5.0	-0.004	139.3	0.974	344.2	1.053
7.0	-0.002	140.3	0.978	345.2	1.103
8.5	0.000	141.3	0.981	354.3	1.110
18.3	0.049	143.0	0.987	357.3	1.128
19.3	0.058	145.0	0.991	360.9	1.148
20.3	0.064	146.5	0.995	364.1	1.161
21.6	0.075	147.6	0.998	366.0	1.168
23.5	0.104	149.1	1.005	378.8	1.224
24.6	0.104	150.0	1.009	381.2	1.235
25.6	0.144	151.0	1.013	382.6	1.241
26.6	0.162	152.0	1.018	384.5	1.251
31.7	0.245	152.8	1.022	386.0	1.258
44.8	0.436	162.3	1.081	387.2	1.265
47.2	0.464	163.8	1.090	388.8	1.272
69.5	0.690	165.0	1.096	390.8	1.280
76.2	0.755	320.0	0.914	392.4	1.295
90.5	0.859	330.3	0.979	403.0	1.348
92.3	0.872	331.1	0.984	406.0	1.363
93.6	0.881	332.0	0.989	408.3	1.375
96.2	0.899	333.0	0.995	410.3	1.383
98.2	0.912	335.1	1.008	412.0	1.390
102.8	0.929	336.2	1.013	413.1	1.395
114.5	0.938	337.1	1.018	416.0	1.407
117.1	0.934	338.2	1.023	426.3	1.465
120.0	0.932	339.0	1.029	428.7	1.478
123.4	0.932	340.1	1.036	432.3	1.496
125.0	0.933	341.5	1.042	434.3	1.503
126.2	0.935	342.5	1.046	438.0	1.515
127.2	0.939			450.3	1.574
128.0	0.942			452.2	1.584
138.3	0.970			454.3	1.595

TABLE XIII(B)

HEAVE VALUES FOR TEST 10.

TIME Hr.	HEAVE In.	TIME Hr.	HEAVE In.
6.0	0.080	112.6	0.234
16.5	0.150	113.7	0.234
19.0	0.163	115.6	0.235
21.6	0.175	117.5	0.235
24.0	0.179	119.4	0.235
26.4	0.180	121.4	0.235
30.0	0.191	126.2	0.235
40.4	0.216	136.4	0.235
42.5	0.217	138.4	0.236
46.0	0.217	141.3	0.236
50.5	0.218	143.4	0.236
54.7	0.219	145.6	0.238
67.3	0.221	148.9	0.249
71.0	0.221	153.5	0.278
74.9	0.222	160.5	0.342
78.9	0.223	163.0	0.367
88.5	0.224	165.5	0.390
90.5	0.224	167.9	0.411
93.5	0.224	169.2	0.421
95.5	0.225	171.7	0.443
97.4	0.225	173.4	0.456
99.6	0.226	174.3	0.463
101.7	0.228		

TABLE XIII (C)

HEAVE VALUES FOR TEST 11.

TIME Hr.	HEAVE In.	TIME Hr.	HEAVE In.	TIME Hr.	HEAVE In.
7.0	0.130	275.0	0.823	718.7	1.093
11.0	0.211	287.5	0.852	729.2	1.120
14.6	0.249	292.0	0.858	742.8	1.140
22.7	0.341	297.6	0.866	752.6	1.151
27.7	0.368	301.3	0.869	769.4	1.180
29.8	0.378	310.5	0.880	779.4	1.201
33.8	0.401	316.1	0.884	790.5	1.216
46.8	0.454	334.7	0.902	891.2	1.256
49.7	0.455	340.8	0.913	900.7	1.257
53.3	0.453	345.5	0.921	910.6	1.266
56.7	0.472	349.5	0.929	916.3	1.272
60.6	0.490	358.9	0.938	921.3	1.274
71.0	0.553	364.8	0.942	934.7	1.308
75.8	0.567	369.6	0.946	939.9	1.318
80.6	0.575	382.7	0.959	945.8	1.325
84.0	0.581	390.7	0.969	958.4	1.343
94.7	0.619	397.0	0.975	963.1	1.349
99.8	0.625	406.6	0.989	972.2	1.359
102.7	0.626	417.3	0.997	982.6	1.372
170.0	0.480	430.5	1.013	987.2	1.376
175.3	0.473	437.0	1.023	996.6	1.386
181.1	0.484	445.8	1.036	1006.6	1.395
191.1	0.557	455.0	1.033	1011.1	1.399
195.9	0.579	462.3	1.034	1014.9	1.402
201.6	0.599	583.0	0.816	1020.4	1.406
214.8	0.675	598.5	0.888	1030.6	1.417
219.7	0.696	612.5	0.946	1035.3	1.423
223.7	0.706	623.7	0.983	1043.6	1.431
227.1	0.714	633.2	1.012	1054.6	1.441
238.5	0.747	649.7	1.046	1066.0	1.452
244.8	0.759	670.5	1.056	1078.7	1.468
250.4	0.761	680.5	1.059	1091.3	1.480
262.7	0.797	694.7	1.085	1127.1	1.515
265.8	0.806	700.0	1.093	1155.4	1.538
270.7	0.813				

TABLE XIII (D)

HEAVE VALUES FOR TESTS 12-12F

Test 12

TIME Hr.	HEAVE In.
2.2	-0.004
5.0	-0.005
17.4	0.000
19.4	0.001
22.9	0.001
25.3	0.001
29.3	0.007
41.5	0.187
42.8	0.206
44.5	0.222
46.1	0.218
47.5	0.189
49.0	0.147
55.0	0.101
65.5	0.097
67.3	0.096
70.0	0.095
72.0	0.096
74.0	0.099
77.3	0.115
79.1	0.155
89.5	0.353
90.0	0.359
91.3	0.361
92.5	0.357
94.1	0.367
95.1	0.416
96.0	0.432
99.2	0.483
100.2	0.498
113.5	0.686
114.5	0.702
115.5	0.719

Test 12A

TIME Hr.	HEAVE In.
5.5	0.000
7.5	0.051
8.5	0.085
10.2	0.145
11.3	0.198
11.8	0.220
14.4	0.291
23.4	0.450

Test 12B

TIME Hr.	HEAVE In.
3.0	0.000
5.0	0.011
6.0	0.033
7.2	0.065
8.1	0.098
10.4	0.152
12.0	0.249
13.5	0.280
23.5	0.458
24.0	0.469

Test 12C

TIME Hr.	HEAVE In.
3.7	0.000
6.4	0.021
12.6	0.289
19.4	0.407
20.0	0.416
21.0	0.434
22.0	0.448
23.0	0.464
24.0	0.477

Test 12D

TIME Hr.	HEAVE In.
5.8	0.006
6.5	0.026
7.3	0.051
9.1	0.095
10.6	0.195
11.0	0.217
12.0	0.281
13.0	0.342
13.5	0.366
23.0	0.696
23.5	0.706

Test 12E

TIME Hr.	HEAVE In.
4.7	0.003
7.8	0.058
9.6	0.128
20.6	0.519
21.4	0.544
22.5	0.569
23.4	0.595

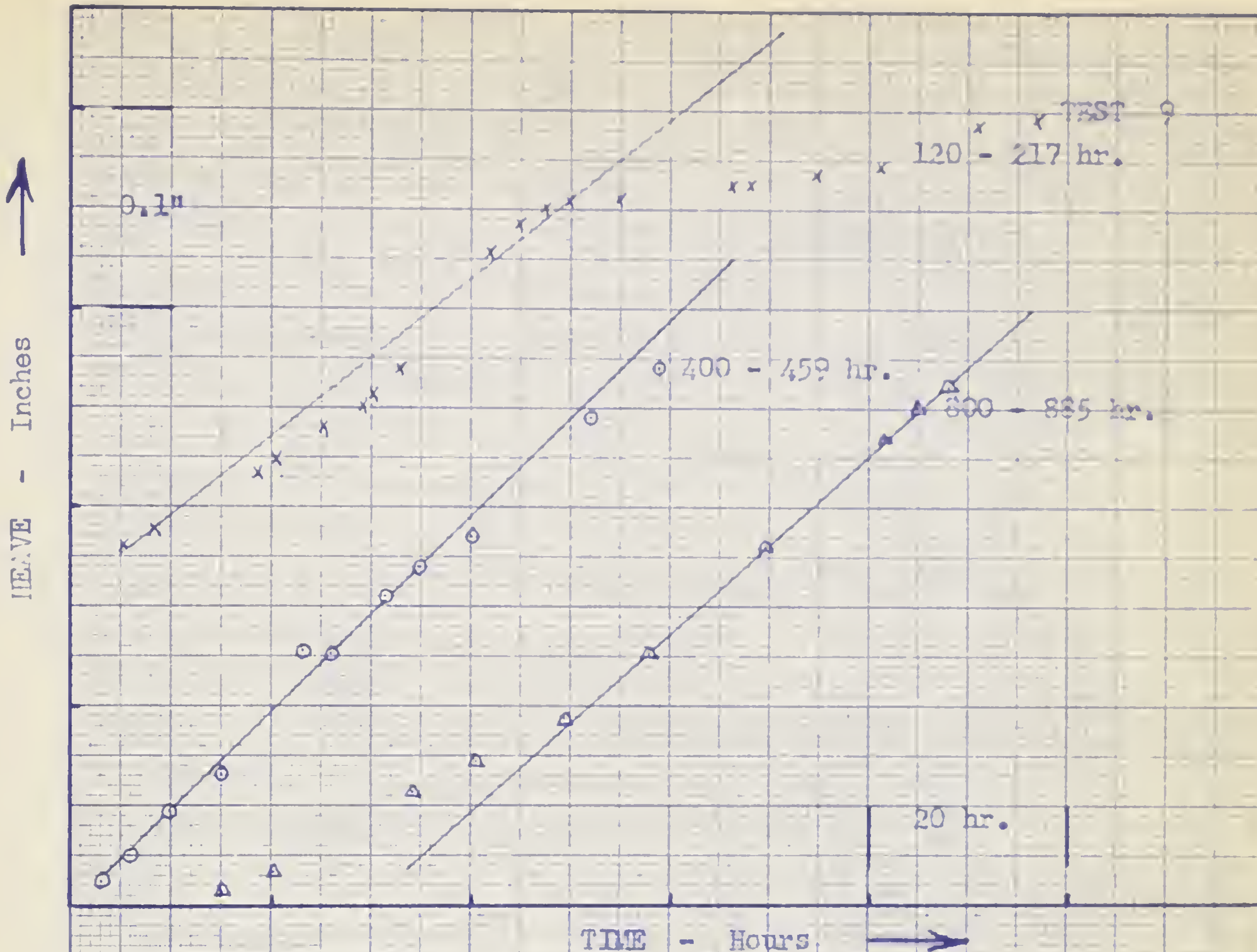
Test 12F

TIME Hr.	HEAVE In.
7.0	0.007
17.5	0.254
18.3	0.276
19.5	0.319
20.0	0.332
20.5	0.349
20.8	0.356
22.3	0.394
23.0	0.412

TABLE XIII (E)

HEAVE FOR TESTS 13-13C

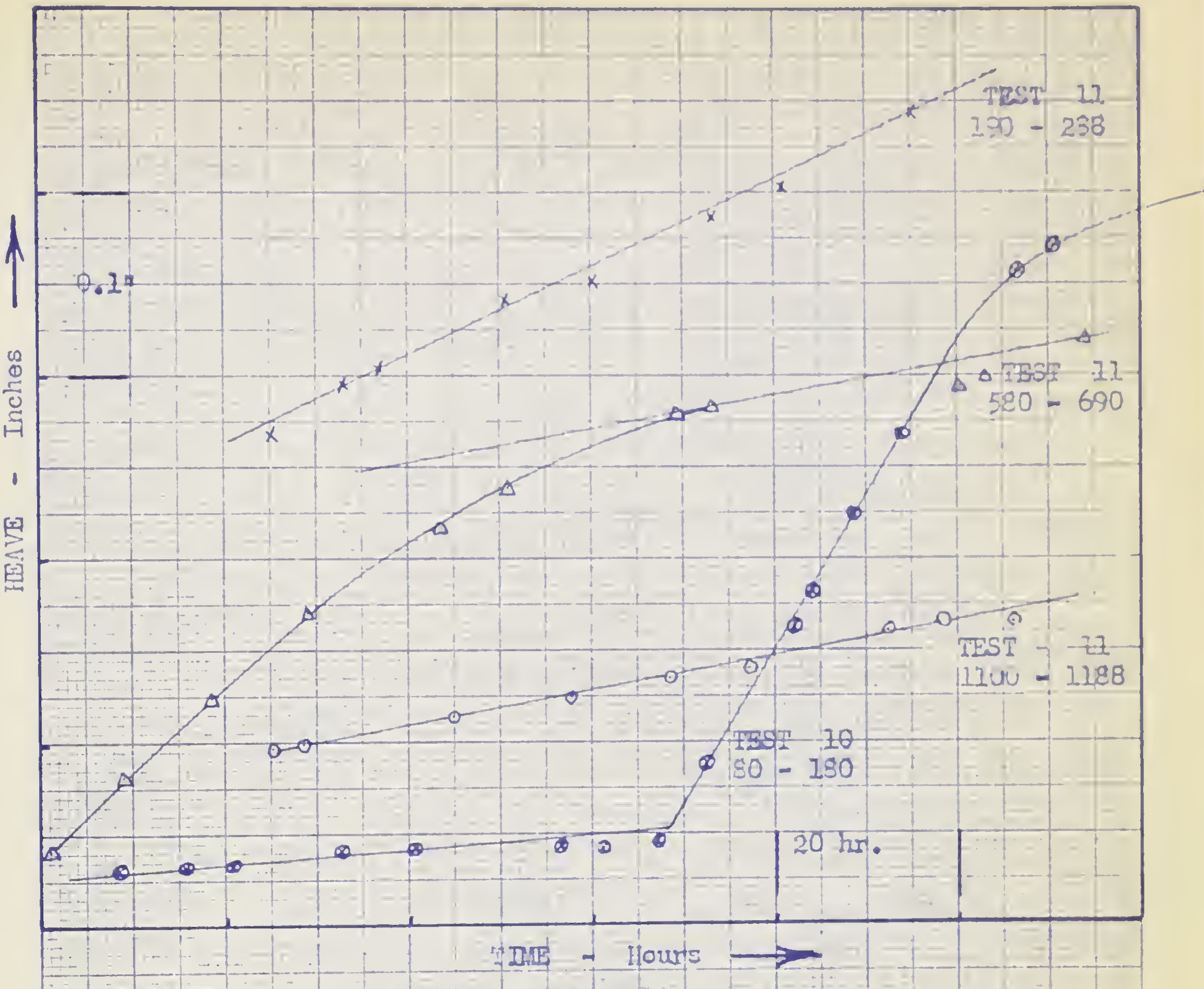
TIME Hr.	HEAVE In.	TIME Hr.	HEAVE In.	TIME Hr.	HEAVE In.
Test 13		48.5	0.703	36.0	0.632
8.8	0.001	49.6	0.717	46.0	0.709
20.5	0.074	50.5	0.728	47.3	0.723
21.7	0.138	52.5	0.757	49.4	0.742
23.1	0.169	53.5	0.774	52.0	0.769
24.5	0.198	54.5	0.788	54.5	0.787
25.7	0.226	55.5	0.800	57.2	0.813
28.0	0.270	59.7	0.845	70.0	0.891
28.8	0.282	62.1	0.870	76.3	0.964
44.5	0.508	71.5	0.931	78.5	0.981
47.2	0.536	72.5	0.938	83.0	1.021
49.2	0.553	73.5	0.944	97.3	1.130
51.5	0.574	74.5	0.950	99.0	1.151
53.0	0.585	76.2	0.967	100.5	1.173
55.2	0.606	77.5	0.975	110.0	1.312
57.2	0.622	79.8	0.976	118.2	1.426
68.5	0.705	95.8	0.977		
69.8	0.712	98.1	1.009	Test 13C	
72.0	0.721	100.2	1.045	20.6	0.610
73.2	0.722	101.4	1.066	22.0	0.634
74.6	0.730	102.5	1.087	23.6	0.668
		107.6	1.295	25.5	0.706
Test 13A		108.0	1.300	27.5	0.736
6.4	0.017	108.8	1.311	29.1	0.755
8.2	0.072			33.0	0.784
10.1	0.115	Test 13B		44.6	0.936
12.6	0.205	6.5	0.022	47.5	0.975
23.5	0.446	10.0	0.140	53.0	1.001
25.4	0.464	12.0	0.162	56.5	1.025
26.2	0.473	22.1	0.421	68.5	1.045
27.0	0.483	23.1	0.442	73.2	1.120
28.2	0.496	24.0	0.460	75.1	1.140
29.1	0.504	25.2	0.476	76.2	1.146
29.8	0.510	26.6	0.505	79.0	1.187
32.0	0.528	27.7	0.520	81.0	1.210
34.3	0.554	29.0	0.545	82.0	1.222
36.1	0.578	30.6	0.567	83.0	1.234
38.1	0.603	34.0	0.609	84.0	1.252
47.5	0.693	35.0	0.622	85.0	1.269



TIME hr.	RATE OF HEAVE Cm. Per Hour
120 - 217 hr.	0.009
400 - 459	0.013
800 - 885	0.011

PLATE 34A

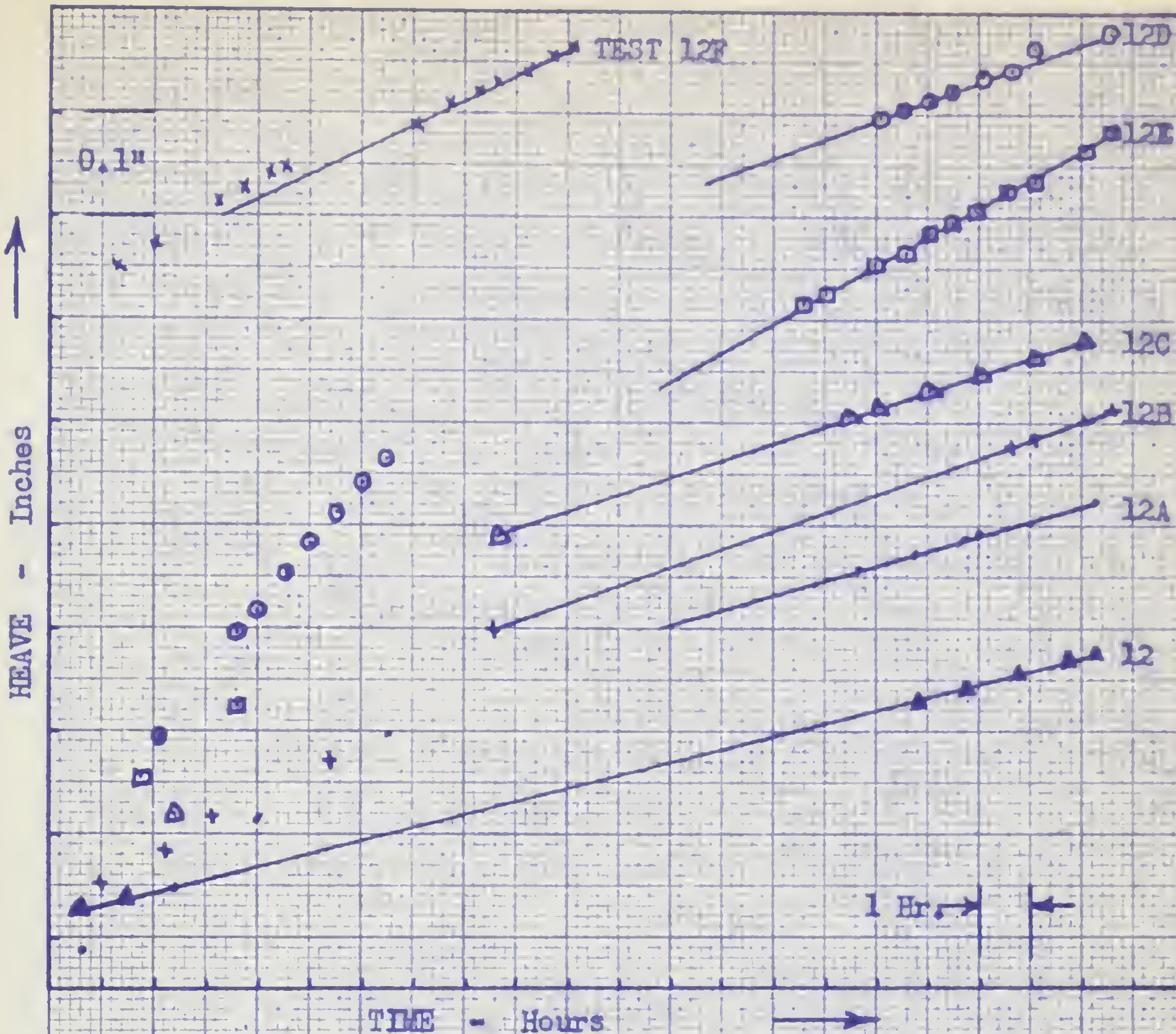
HEAVE CURVES



TEST	TIME hr.	RATE OF HEAVE Cm. Per Hour
10	80 - 148	0.001
10	148 - 180	0.032
11	190 - 238	0.005
11	580 - 690	0.002
11	1100 - 1188	0.002

PLATE 34 B

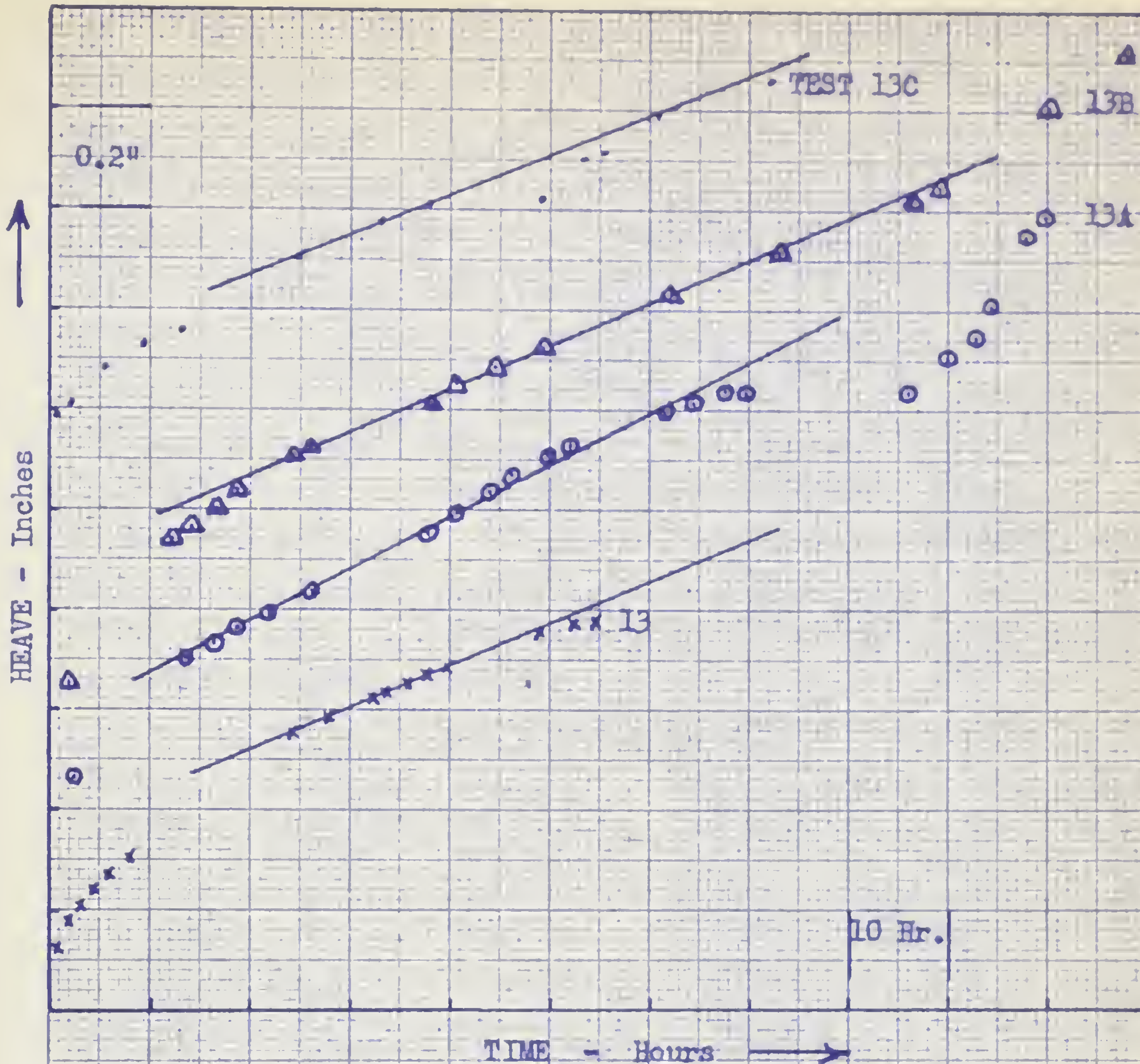
HEAVE CURVES



TEST	RATE OF HEAVE Cm. Per Hour
12	0.032
12A	0.036
12B	0.044
12C	0.041
12D	0.047
12E	0.070
12F	0.061

PLATE 34C

HEAVE CURVES



TEST	RATE OF HEAVE Cm. Per Hour
13	0.021
13A	0.026
13B	0.022
13C	0.020

PLATE 34 D

HEAVE CURVES

TABLE XIV

DISTANCE FROM WATER RESERVOIR TO FROST LINE FOR VARIOUS RATES OF HEAVE

TEST	TIME hr.	DEPTH OF FROST LINE in.	RESERVOIR TO FROST LINE in.	RATE OF HEAVE cm./hr.
9	120-217	8.4-8.9	16.0-15.5	0.009
"	400-459	9.4-9.6	15.0-14.8	0.013
"	800-885	10.2-11.4	14.2-13.0	0.011
10	80-148	8.8-11.0	15.7-13.5	0.001
"	148-180	11.0-12.0	13.5-12.5	0.022*
11	190-288	4.2-5.9	20.3-18.6	0.005
"	620-690	7.8-8.1	16.7-16.4	0.002
"	1100-1188	10.2-10.9	14.3-13.6	0.002
12	97-117	1.0-1.4	6.6-7.0	0.032
12A	23.28	2.9	5.1	0.036
12B	12.25	1.2-3.0	6.8-5.0	0.044
12C	13-24	1.5-3.3	6.5-4.7	0.041
12D	23-25	3.1	4.9	0.047
12E	21-28	2.5-3.0	5.5-5.0	0.070
12F	22-25	3.5	4.5	0.061
13	45-65	2.6-3.8	12.4-11.2	0.021
13A	25-75	2.7-6.0	12.3-9.0	0.026
13B	35-100	5.5-9.5	9.5-5.5	0.022
13C	50	5.4	9.6	0.020

* The frost line had penetrated the silt.

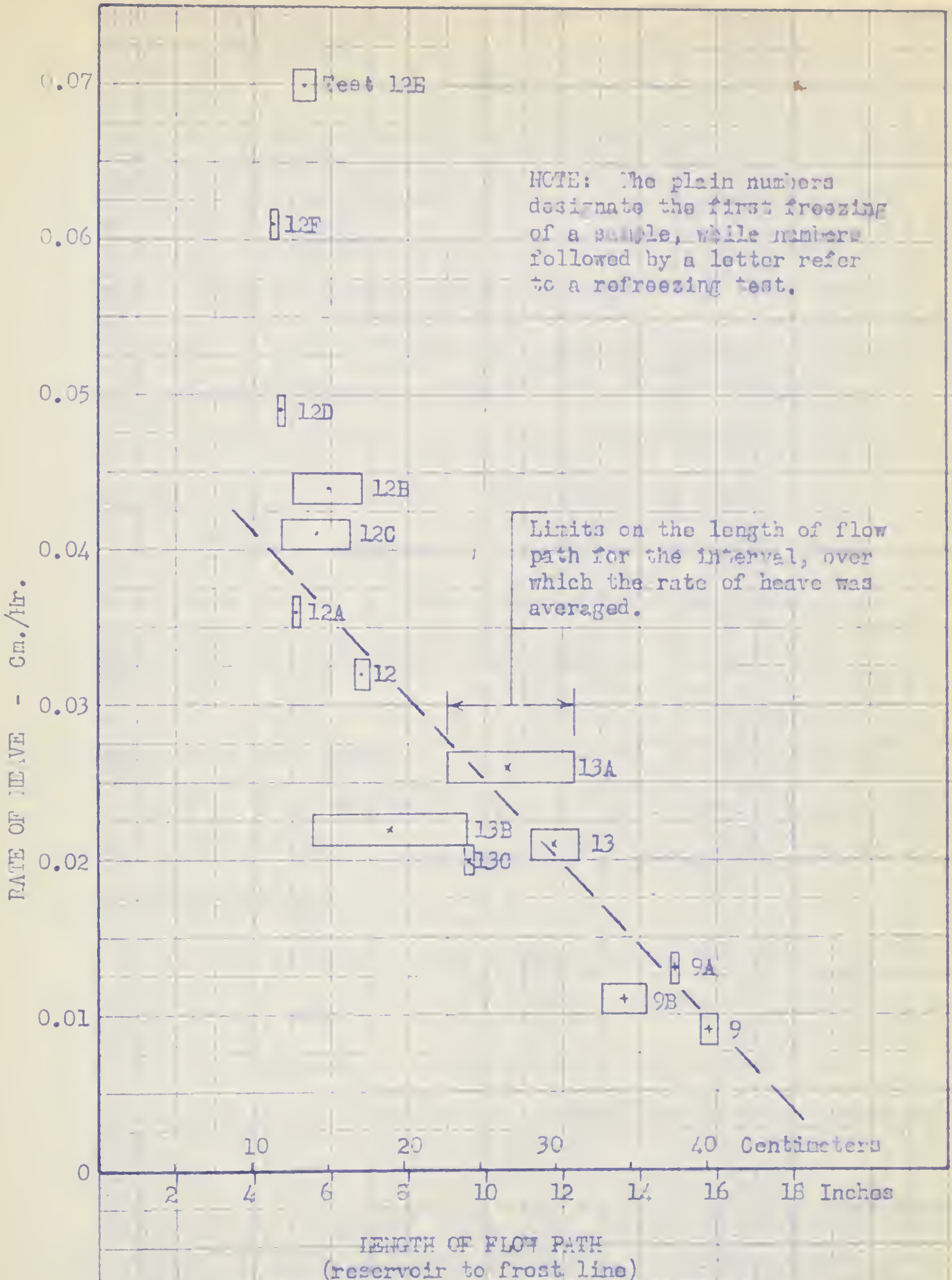


PLATE 35

RATE OF HEAVE AS AFFECTED BY
THE LENGTH OF FLOW PATH
AND REFREEZING

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. The fluctuations of the heave, depth of frost line and piezometric pressure values that were observed in the frost heave tests, appear to support Martin's "rhythmic ice banding" hypothesis.

2. The magnitude of the fluctuations tended to increase as the rate of penetration of the frost line decreased, indicating an increasing instability in factors controlling the moisture flow.

3. An "overall steady-state" condition appeared to exist where, averaged over an extended period of time, the fluctuating quantities could be defined by increasing linear functions of time.

4. The piezometric pressures exceeded the capillarity of the material in the late stages of one test and in the vicinity of the frost line. As these data were excluded from the pressure analysis, the flow characteristics obtained could not be attributed to the entry of air into the specimen.

5. It was found that after taking into account variations in the viscosity and void ratio along the flow path, the characteristics of the moisture movements in the frost heave tests could not be explained in terms of Darcy type flow, despite the fact that the degree of saturation remained constant at 96%.

6. A comparison of the frost heave test results with published data indicated a similarity in the hydrodynamics whether the water was removed from the specimen by an ice lens, evaporation, or by an applied negative pore pressure.

7. The fact that the experimental pressure-permeability data can be fitted by a curve of the type $k_u = a/(h^n + b)$ indicates that the "unsaturated" flow theory may apply to the moisture movements that occur during ice segregation.

8. There are insufficient data to indicate whether the small n-value that produced the best fitting curve is due to the specimen material or the conditions imposed during the frost heave tests.

9. For the material tested, first cycle freezing indicated that the rate of heave was inversely proportional to the distance between the water reservoir and the frost line.

10. The rate of heave tended in increase with each cycle of freezing. No maximum was established at the end of seven cycles.

Recommendations

Further investigation should be carried out with respect to the application of "unsaturated" flow theory to the frost heave problem. Frost heave tests on a variety of materials would help to establish the range of n-values that apply to the pressure-permeability curves for flow due to ice segregation. The possibility of obtaining solutions to the flow equation (V.23), other than those given by Gardner (31), should be investigated. It would be possible to check the validity of "unsaturated" flow theory for the case of moisture movements due to ice segregation, once solutions to the flow equation were available corresponding to n-values determined from the experimental pressure-permeability data.

It is suggested that the influence of temperature on the flow characteristics can be determined by comparing data from an evaporation

test with that from a frost heave test on the same material. It is possible that such tests could be carried out concurrently on the same specimen.

As the instrumentation required makes it difficult to compact the test specimens, it is suggested that consolidation effects during the test could be reduced by letting the sample consolidate under a surcharge prior to the application of freezing temperatures. For non-swelling materials, a surcharge of the same order of magnitude as the maximum effective stresses anticipated should eliminate most of the void ratio variation.

In frost heave testing it would be desirable to measure the rate at which water enters the specimen. By comparing this quantity with the rate of heave it could be determined if the flow as steady-state or not.

The apparatus should be modified to permit the removal of the specimen at the end of the test. This would allow the frozen portion to be inspected for the location of ice lenses. The unfrozen portion could be immediately sectioned to determine the moisture contents corresponding to the terminating pressure conditions.

It is suggested that the possibility of using some electrical resistance method to determine the moisture content in the test specimen during the test be investigated. By obtaining moisture content measurements at the manometer tapping points, the moisture-tension relationships could be obtained from the frost heave tests.

Frost heave tests with pressure measurements should be tried using various additives to see if changes in such characteristics as viscosity and surface tension are reflected in the pressure readings.

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APPENDIX "A"

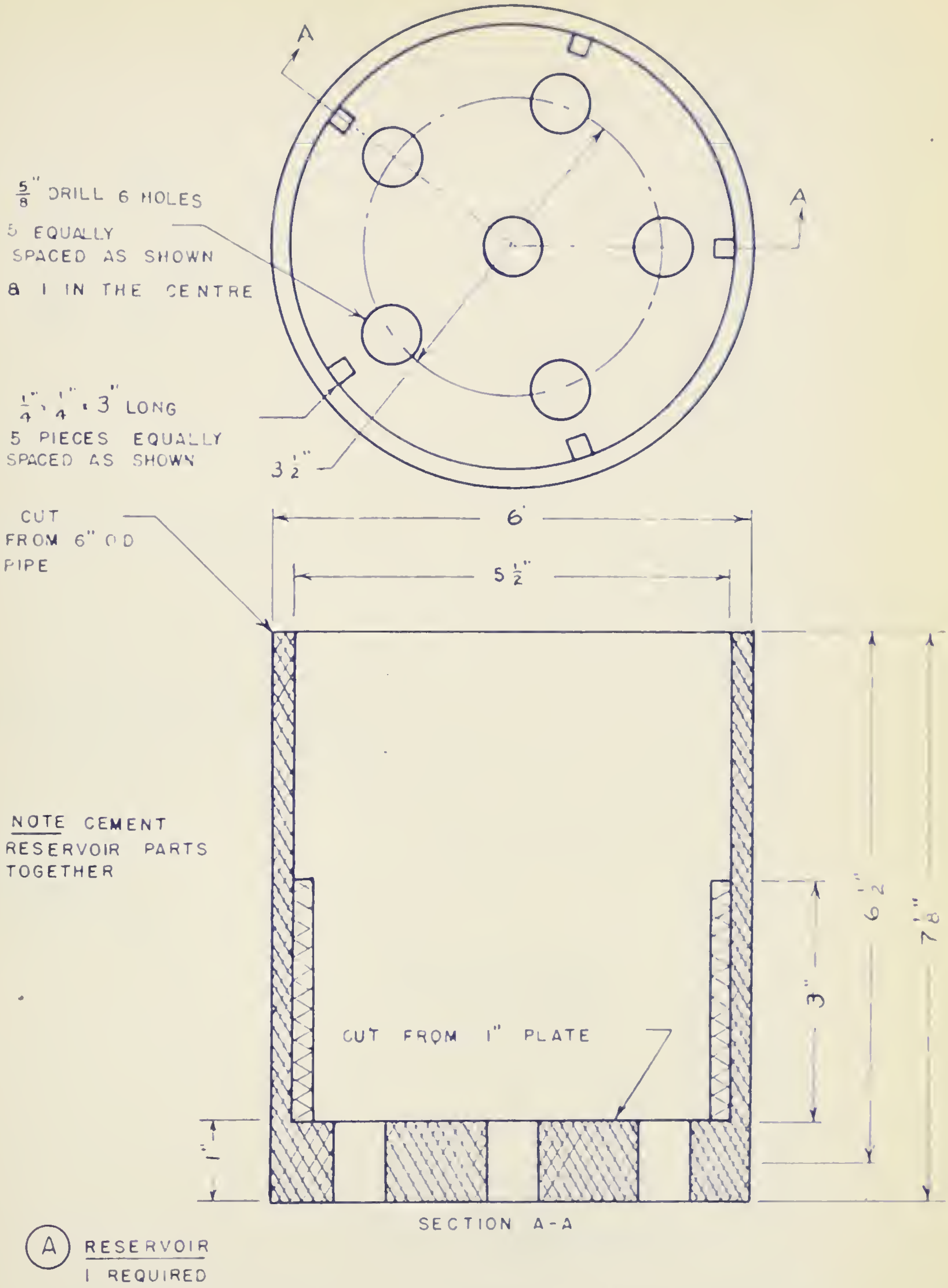


PLATE 36A

DETAILED DRAWING No 1

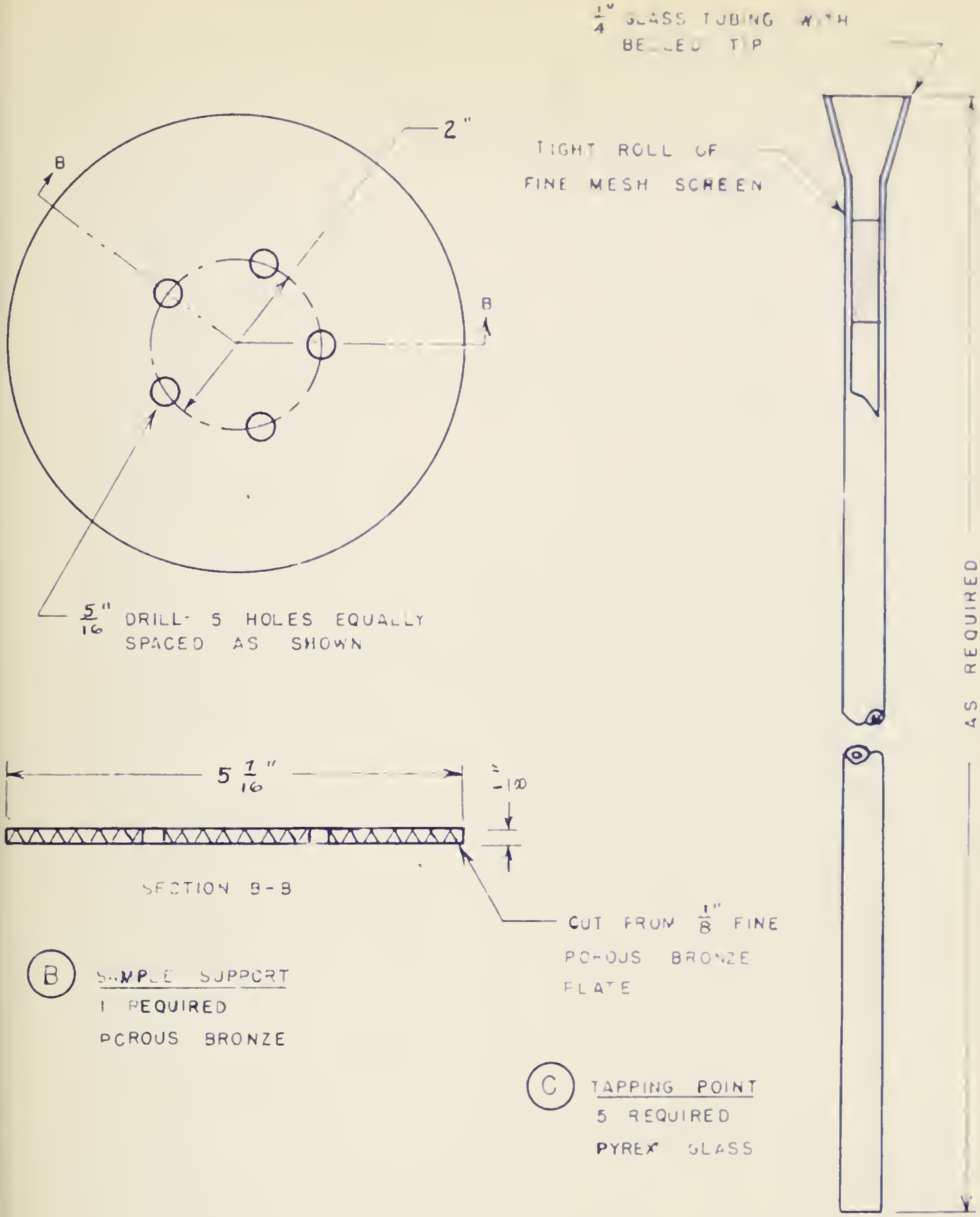
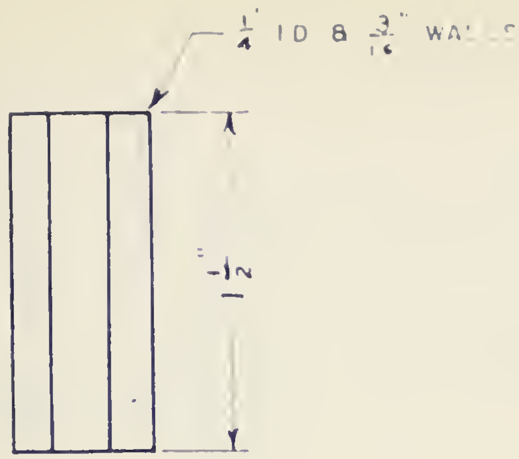
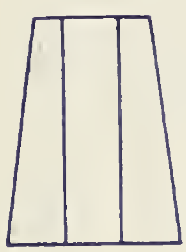


PLATE 36 B

DETAIL DRAWING No 2



(E) COUPLING
5 REQUIRED
RUBBER TUBING

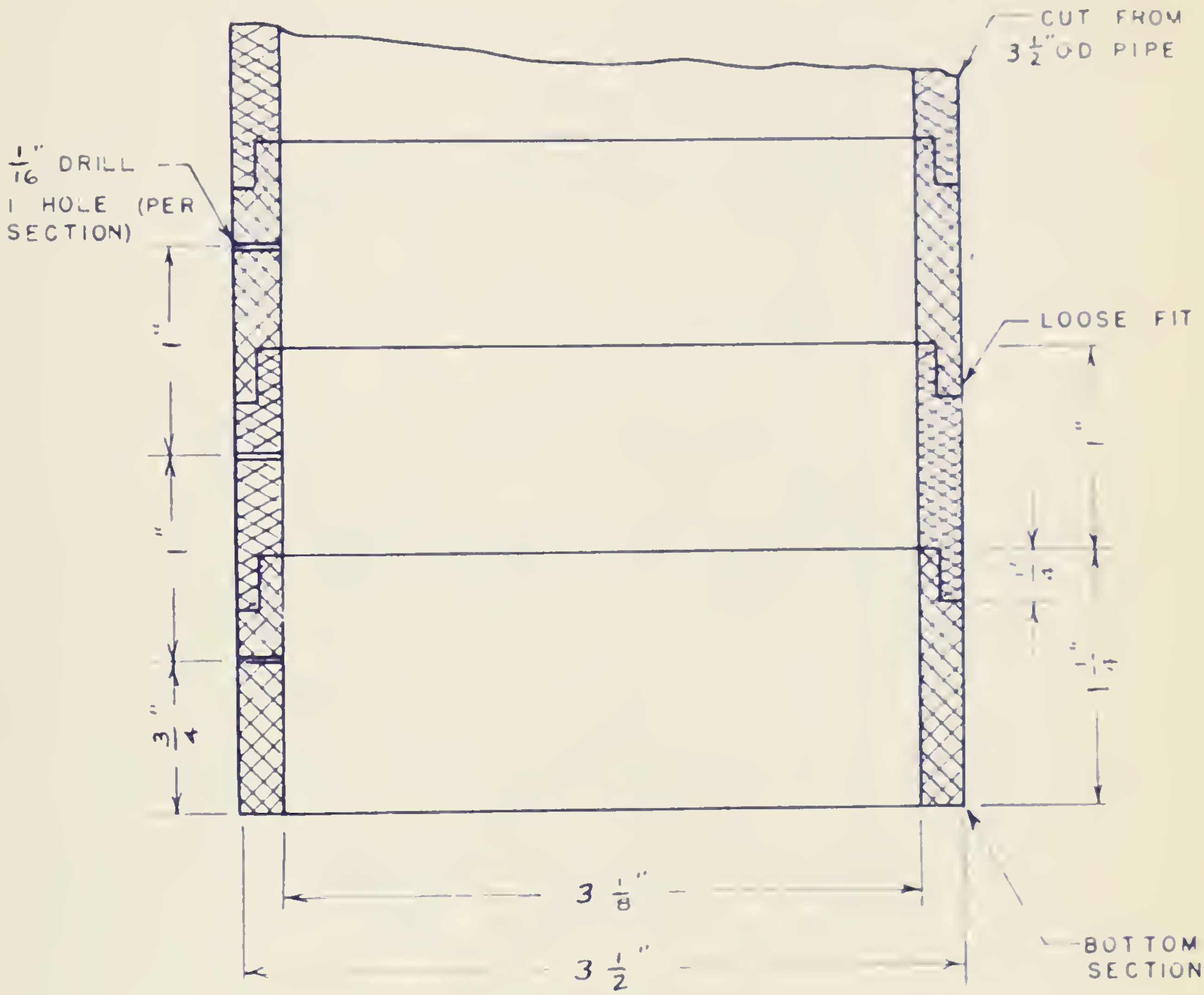


(F) RUBBER STOPPERS
NO. 1
6 REQUIRED

(D) MANOMETER PART
5 REQUIRED
PYREX GLASS

PLATE 36 C

DETAIL DRAWING No 3



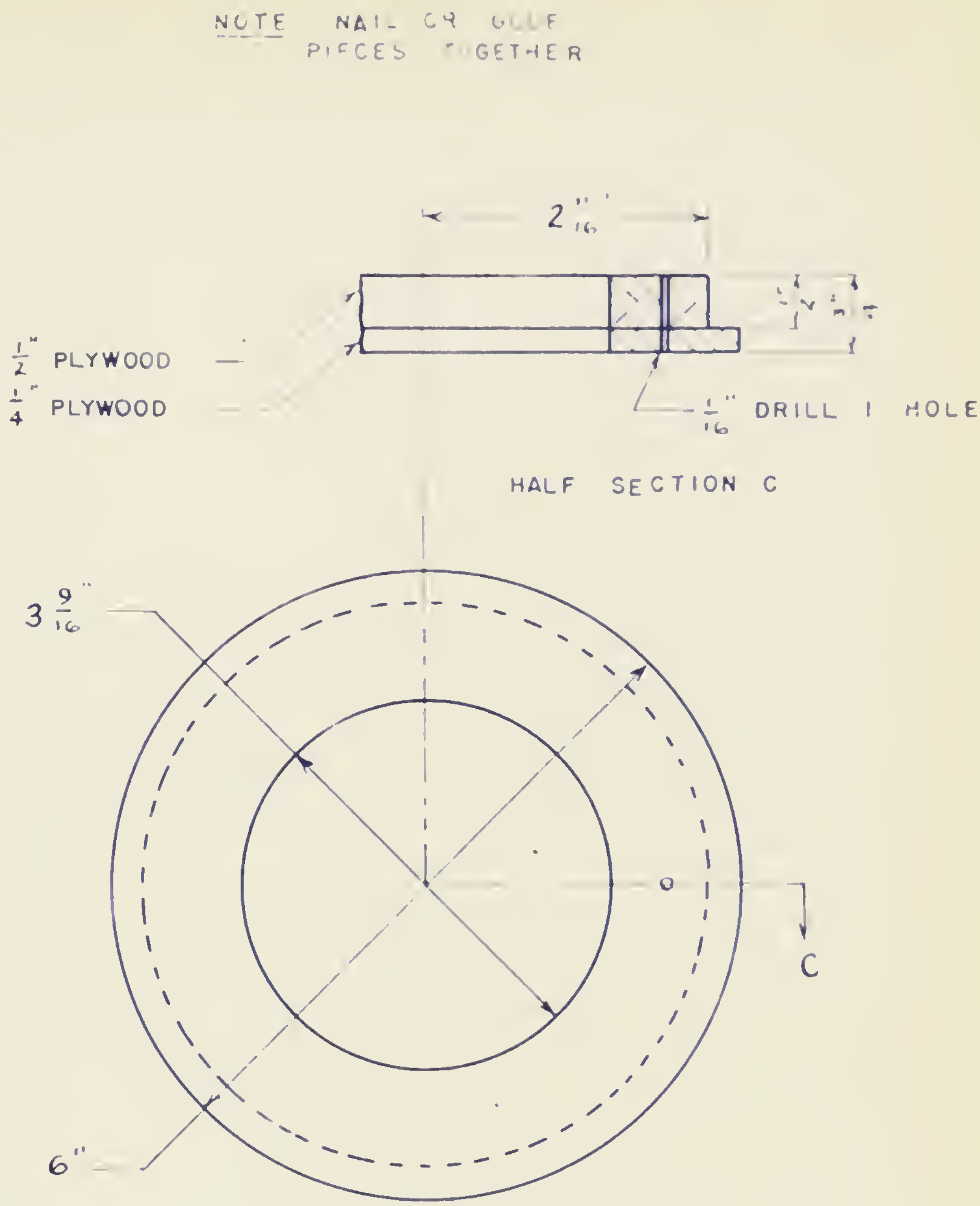
(G) SAMPLE CONTAINER

1 BOTTOM & 23 REGULAR SECTIONS REQUIRED

LUCITE F A O

PLATE 36 D

DETAILED DRAWING No 4



(H) RESERVOIR CAP

1 REQUIRED

PLYWOOD

PLATE 36 E

DETAILED DRAWING No. 5

APPENDIX "B"

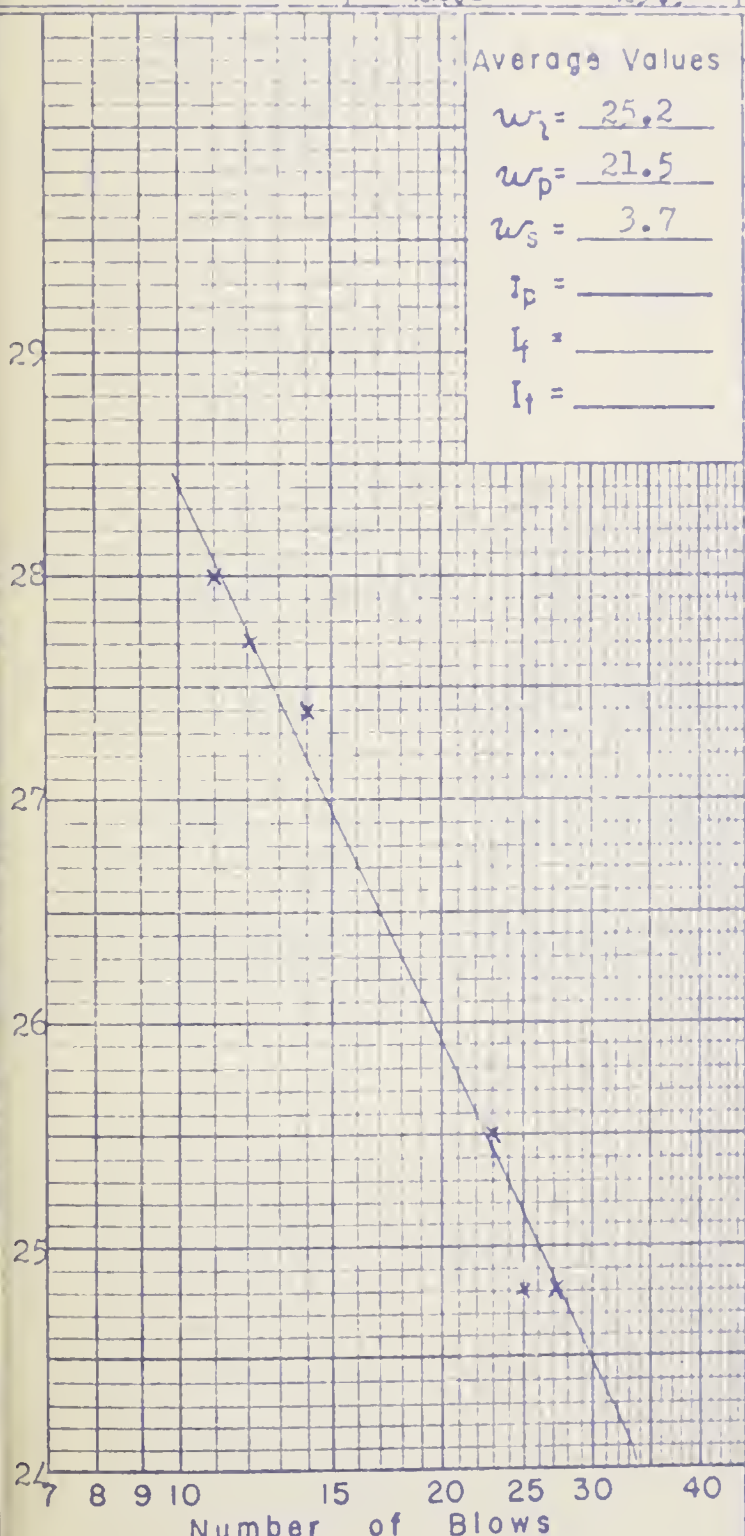
UNIVERSITY of ALBERTA
DEP'T of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY

ATTERBERG LIMITS

PROJECT	
SITE	
SAMPLE	SILT (2)
LOCATION	
HOLE	DEPTH
TECHNICIAN	DATE

Liquid Limit

Trial No.	1	2	3	4	5	6
No. of Blows	27	23	25	14	12	11
Container No.	V26	V22	V5	V3	[illegible]2	V21
Wt. Sample Wet + Tare	82.8514	81.6669	71.4465	75.7723	81.1934	8[illegible].5025
Wt. Sample Dry + Tare	80.9972	79.6965	70.2098	73.2513	78.8341	[illegible]3.[illegible]720
Wt. Water	1.8542	1.9704	1.2367	2.5210	2.3593	2.2305
Tare Container	73.5156	71.9736	65.2289	64.0741	70.3142	73.0865
Wt. of Dry Soil	7.4816	7.7229	4.9809	9.1772	8.5199	10.[illegible]55
Moisture Content w%	24.8	25.5	24.8	27.4	27.7	2[illegible].0



Average Values

w_l = 25.2

w_p = 21.5

w_s = 3.7

I_p = ______

I_l = ______

I_t = ______

Plastic Limit

Trial No.	1	2	3
Container No.	1	4	5
Wt. Sample Wet + Tare	38.6706	38.9235	36.6[illegible]7[illegible]
Wt. Sample Dry + Tare	38.4592	38.7199	36.513[illegible]
Wt. Water	0.2114	0.2036	[illegible].1[illegible]39
Tare Container	37.4682	37.7511	35.6[illegible]
Wt. of Dry Soil	0.9910	0.9688	0.[illegible]331
Moisture Content %	21.3	21.0	22.[illegible]

Shrinkage Limit

Trial No.			
Container No.			
Wt. Sample Wet + Tare			
Wt. Sample Dry + Tare			
Wt. Water			
Tare Container			
Wt. of Dry Soil W_o			
Moisture Content w%			
Vol. Container V			
Vol. Dry Soil Pat V_o			
Shrinkage Vol. $V - V_o$			
Shrinkage Limit w_s			

$$w_s = w - \left(\frac{V - V_o}{W_o} \times 100\right)$$

Description of Sample: Slightly plastic silt. According to the Airfield Classification System it is ML.

Remarks: The sample had been air dried prior to being used in this test.

UNIVERSITY of ALBERTA
DEP'T. of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY

HYDROMETER TEST

PROJECT
SITE
SAMPLE SILT (2)
LOCATION
HOLE DEPTH
TECHNICIAN DATE

Date	Temp. °C.	Time	Elapsed Time	R'_h	$R_h = R'_h + c_m$	D m.m.	$R_h + m_t - c_d$	W %	W % Basis Orig Sample	Remarks
ec. 11		0920	30s	28.8	29.1	0.053	29.1	68.0		
"			1m	27.5	27.3	0.042	27.3	64.0		
"			2m	25.3	25.6	0.030	25.6	60.0		
"	21.5		4m	23.9	24.2	0.021	24.2	56.6		
"	21.4		8m	17.0	17.3	0.016	17.3	40.5		
"	"		15m	14.0	14.3	0.013	14.3	33.4		
"	"	0950	30m	9.9	10.2	0.0091	10.2	23.8		
"	21.2	1020	1h	7.2	7.5	0.0065	7.4	17.3		
"	21.2	1120	2h	5.3	5.6	0.0048	5.5	12.9		
"	20.5	1320	4h	4.8	5.1	0.0034	4.9	11.5		
ec. 12	19.7	0930	24h	3.2	3.5	0.0014	2.8	6.5		
ec. 13	19.5	0830	47h	2.9	3.2	0.0010	2.5	5.9		

ydrometer No.s 6786 and Graduate No.

$W\% = \frac{100}{W_s} \cdot \frac{S_s}{S_s - 1}(R_h + m_t - c_d) = 2.27 \; (R_h + m_t - c_d)$

eniscus correction = c_m = 0.3 and respectively

ispersing agent used 6% Calgon solution Amount 10 cc.

orrection for change in density of liquid due to addition of dispersing agent = c_d

c_d = 0.3 and respectively

pecific Gravity of Solids = G_s 2.70

escription of Sample
Slightly plastic silt. According to the Airfield Classification System it is an ML.

Method of Preparation
Treated with Hydrogen Peroxide and warmed in oven. Soaked with distilled water over night, then added Calgon.

Remarks Dry weight of the sample used was computed on the basis of the material recovered after the test.

Initial Moisture Content

ontainer No.
t. Sample Wet + Tare
t. Sample Dry + Tare
t. Water
are Container
t. of Dry Soil
itial Moisture w %

Dry Weight of Sample

Container No.
Wt. Sample (~~Wet~~/Dry) + Tare 1359.9 gm.
Tare 1292.0 gm.
Wt. (~~Wet~~/Dry) Soil 67.9
Dry Weight from Initial
Moisture = $\frac{100 \times \text{Wt. Wet Soil}}{100 + \text{Init. Moist. \%}}$ =

PLATE 38

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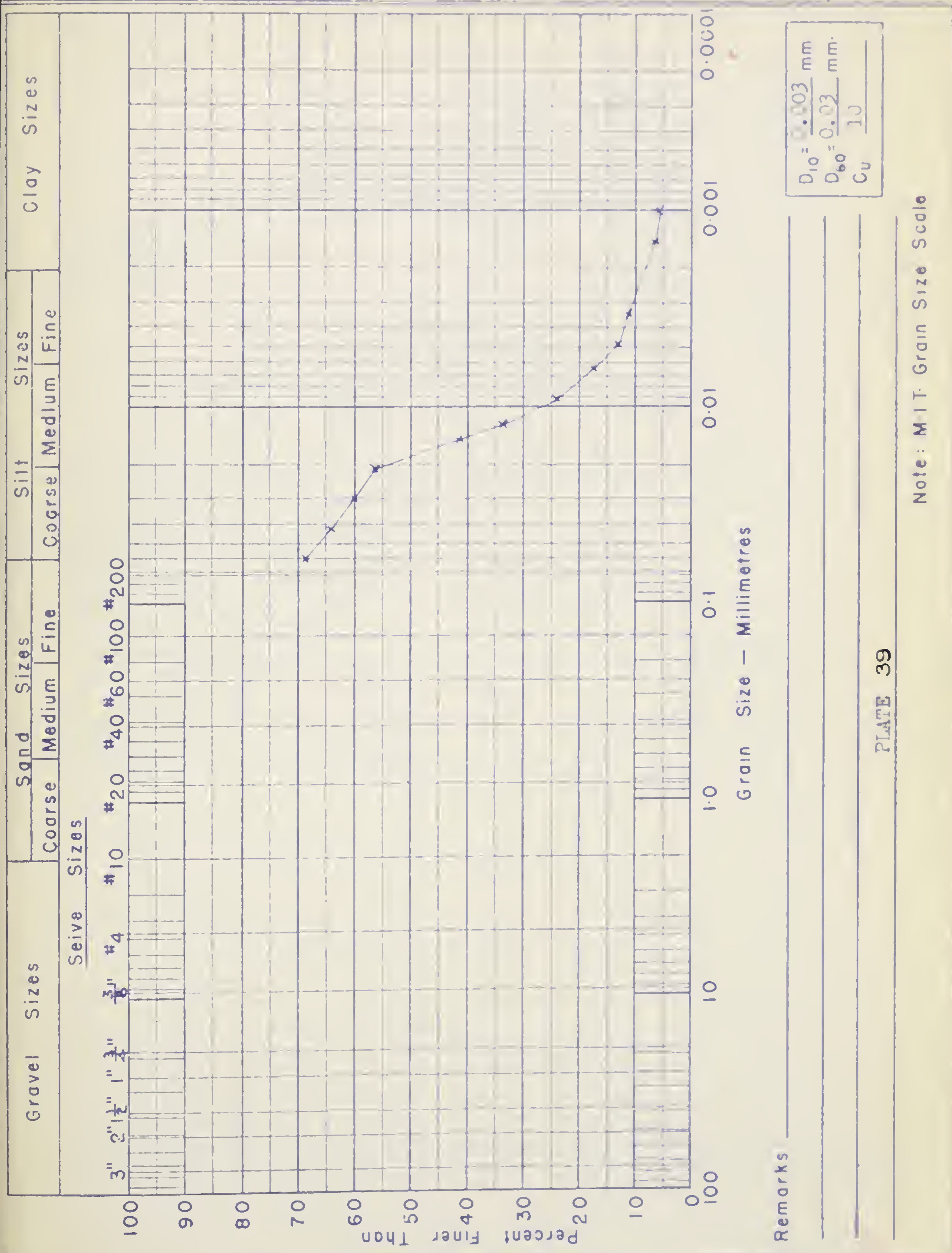
GRAIN SIZE CURVE

PROJECT
SITE
SAMPLE SILT (2)
LOCATION
HOLE DEPTH
TECHNICIAN DATE



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SIEVE ANALYSIS

PROJECT	166
SITE	
SAMPLE	CALGARY GRAVEL (3)
LOCATION	
HOLE	DEPTH
TECHNICIAN	DATE

Total Dry Weight of Sample	Sieve No.	Size of Opening Inches	Size of Opening Mm.	Weight Retained gms.	Total Wt. Finer Than gms.	Percent Finer Than	% Finer Than Basis Orig. Sample
Initial Dry Weight					35 413	100.0	
Retained No. 4		2		8824	26 589	75.1	
Tare No.		1½		2320	24 269	68.6	
Wt. Dry + Tare		1		2790	21 479	60.7	
Tare		¾	19·10	2220	19 259	54.4	
Wt. Dry		⅜	9·52	3031	16 228	45.9	
	4	·185	4·76	3161	13 067	36.9	
Passing	4			13067			
Initial Dry Weight					1 554	100.0	36.9
Passing No· 4	10	·079	2·000	293.6	1 260	81.1	28.1
Tare No·	20	·0331	·840	423.5	836	53.7	19.3
Wt. Dry + Tare	40	·0165	·420	528.7	307	19.8	7.1
Tare	60	·0097	·250	173.9	133	8.6	3.1
Wt. Dry	100	·0059	·149	52.0	81	5.2	1.8
	200	·0029	·074	27.7	53	3.4	1.2
Passing	200			53.4			

Description of Sample According to the Airfield Classification System, this material would be called GF. The PUBLIC ROADS Classification would probably be A - 2.

Time of Sieving 20 minutes

Method of Preparation

Remarks

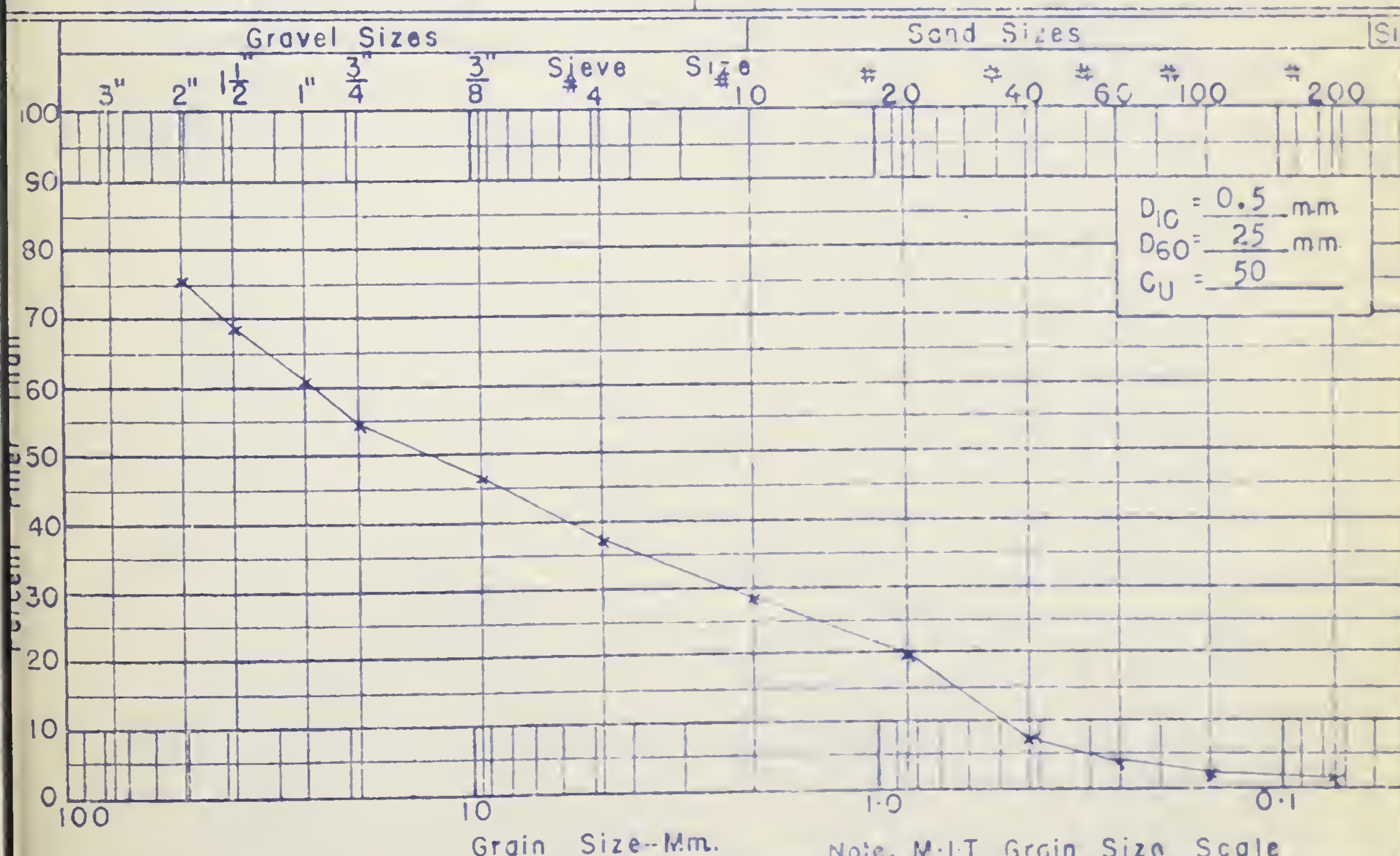

PLATE 40

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SOIL MECHANICS LABORATORY

SIEVE ANALYSIS

PROJECT	167
SITE	
SAMPLE	GRAVEL (4)
LOCATION	
HOLE	DEPTH
TECHNICIAN	DATE

Total Dry Weight of Sample	Sieve No.	Size of Opening Inches	Mm.	Weight Retained gms.	Total Wt. Finer Than gms.	Percent Finer Than	% Finer Than Gross Orig. Sample
Initial Dry Weight Retained No. 4							
Tare No.		1½			4 514	100.0	68.7
Wt. Dry + Tare		1		340	4 174	92.6	63.5
Tare		¾	19·10	291	3 883	86.1	59.0
Wt. Dry		⅜	9·52	379	3 504	77.7	53.2
	4	·185	4·76	403	3 101	68.7	47.1
Passing	4			3 101			
Initial Dry Weight Passing No· 4							
	10	·079	2·000	These values were based on			38.2
Tare No·	20	·0331	·840	the grading found for the minus			25.3
Wt· Dry + Tare	40	·0165	·420	#4 material in the CALGARY			9.3
Tare	60	·0097	·250	GRAVEL	3		4.1
Wt· Dry	100	·0059	·149				2.5
	200	·0029	·074				1.6
Passing	200						

Description of Sample According to the Airfield Classification System, this material would be called GF. The Public Roads Classification would probably be A - 2.

Time of Sieving 20 minutes

Method of Preparation

Remarks This material is the same as CALGARY GRAVEL (3), with an excess of material passing the #4 sieve.

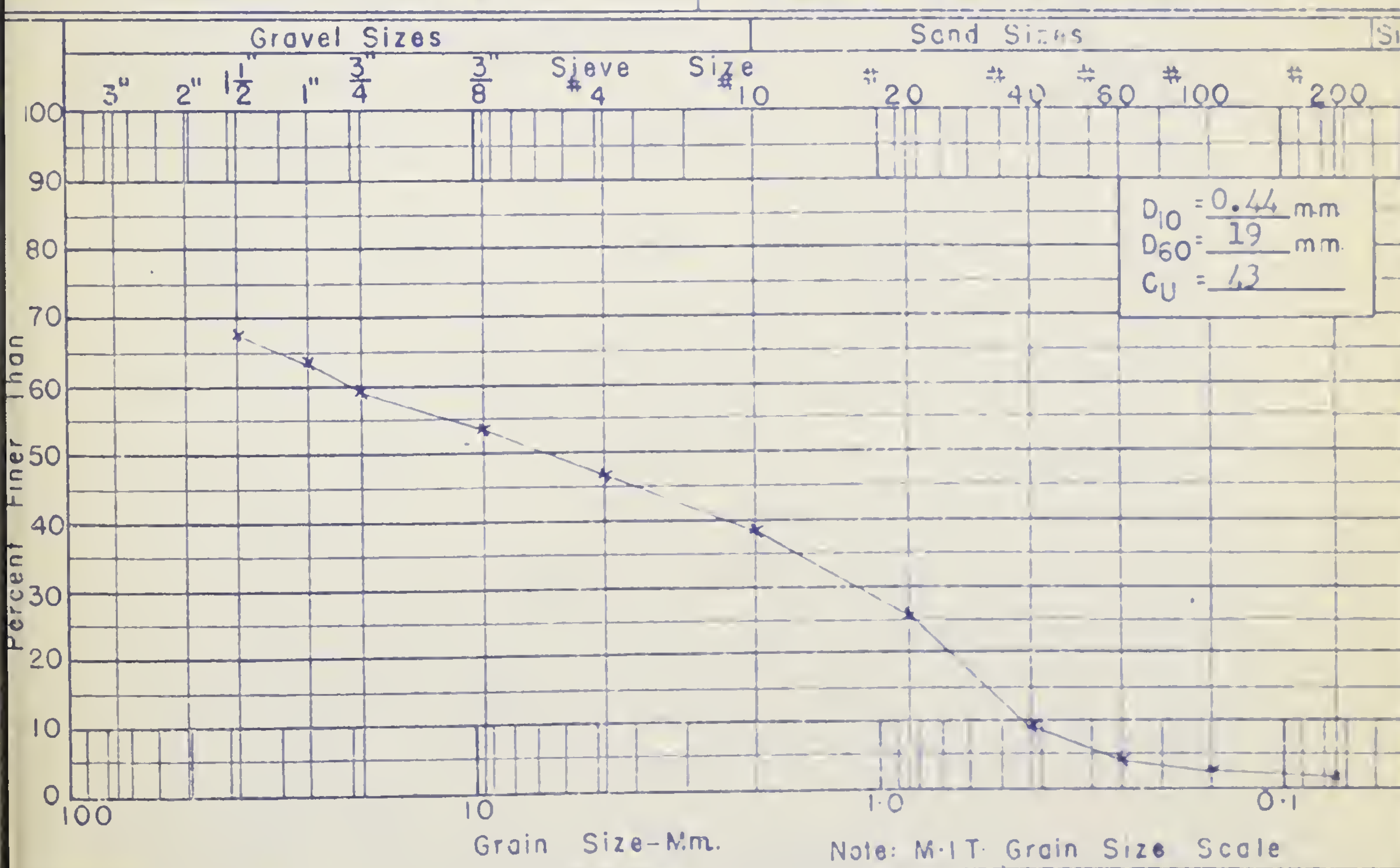

PLATE 41

UNIVERSITY of ALBERTA
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SOIL MECHANICS LABORATORY
CONSOLIDATION DATA

PROJECT 168
SITE
SAMPLE Silt
LOCATION
HOLE DEPTH
TECHNICIAN DATE 20 Jan. 59

Ring Data
Ring No. C3
Weight gm's. 903.0
Thickness ins. 1.50 - 0.45 = 1.05
Diameter ins. 2.60
Area sq. cm's. 34.2

Machine Data
Machine No. 3
Multiplication Factor 100
Wt Block + Stone + Ball gm's. 475

Consolidation Sample Weights
Wt. Tare + Ring + Soil + Water (End) gms 1109.1
Wt Tare + Ring + Soil (End) gms 1080.5
Wt. Tare (Tare No V62) gms 33.6
Wt Ring + Soil + Water (End) gms 1075.5
Wt Ring + Soil + Water (Start) gms 1083.6
Wt Ring + Soil gms 1046.9
Wt. Soil gms 143.9
Water (End) = 28.6 gms. = 19.9 %
Water (Start) = 36.7 gms = 25.5 %

Description of Sample
ML - See Atterberg Limits

Date, Time Load, Dial Remarks	Date, Time Load, Dial Remarks	Date, Time Load, Dial Remarks	Date, Time Load, Dial Remarks	Date, Time Load, Dial Remarks	Date, Time Load, Dial Remarks	Date, Time Load, Dial Remarks
	20 Jan. 59	1m .7363	21 Jan. 59	2m .7080	21 Jan. 59	
	20 gm.	2m 46	20 gm.	4m 80	200 gm.	
	15:05	4m 28	10:45	9m 80	15:47	
	18s .7848	8m 13	6s .7104	21 Jan. 59	6s .7062	
	30s 40	15m 06	12s 06	400 gm.	12s 61	
	1m 22	30m 00	30s 10	11:15	30s 60	
	2m 01	50m .7298	1m 13	6s .7060	2m 60	
	Added water	21 Jan. 59	2m 17	12s 58	4m 59	
	4m .7760	200 gm.	4m 19	30s 54	9m 59	
	8m 06	10:10	8m 20	1m 51	21 Jan. 59	
	15m .7631	12s .7248	21 Jan. 59	2m 50	400 gm.	
	30m .7544	30s 35	50 gm.	4m 49	15:58	
	75m 24	1m 24	10:54	8m 46	6s .7038	
	Covered with	2m 11	6s .7116	15m 44	12s 36	
	water.	4m . 00	12s 15	30m 43	30s 34	
	120m .7519	8m .7192	1m 13	142m 39	1m 32	
	1060m 13	15m 88	2m 11	21 Jan. 59	2m 30	
	21 Jan. 59	21 Jan. 59	4m 11	20 gm.	4m 30	
	50 gm.	400 gm.	6m 11	13:40	8m 29	
	08:45	10:27	21 Jan. 59	12s .7101	15m 28	
	6s .7490	6s .7125	100 gm.	2m 06	21 Jan. 59	
	12s 89	12s 19	11:00	4m 06	20 gm.	
	30s 83	30s 03	6s .7102	75m 06	16:15	
	1m 79	1m .7092	12s 01	110m 06	12s .7063	
	2m 70	2m 81	30s 00	21 Jan. 59	30s 69	
	4m 56	4m 73	1m 00	100 gm.	1m 72	
	8m 40	8m 69	2m 00	15:31	2m 75	
	15m 30	21 Jan. 59	4m .7099	6s .7083	4m 76	
	30m 22	100 gm.	21 Jan. 59	12s 81	8m 78	
	21 Jan. 59	10:40	200 gm.	30s 80	15m 79	
	100 gm.	12s .7082	11:05	1m 79	32m 79	
	09:17	30s 83	6s .7084	2m 78		
	6s .7390	1m 84	12s 83	4m 77		
	12s 85	2m 84	30s 82	8m 76		
	30s 74	4m 84	1m 81	15m 76		

PLATE 42

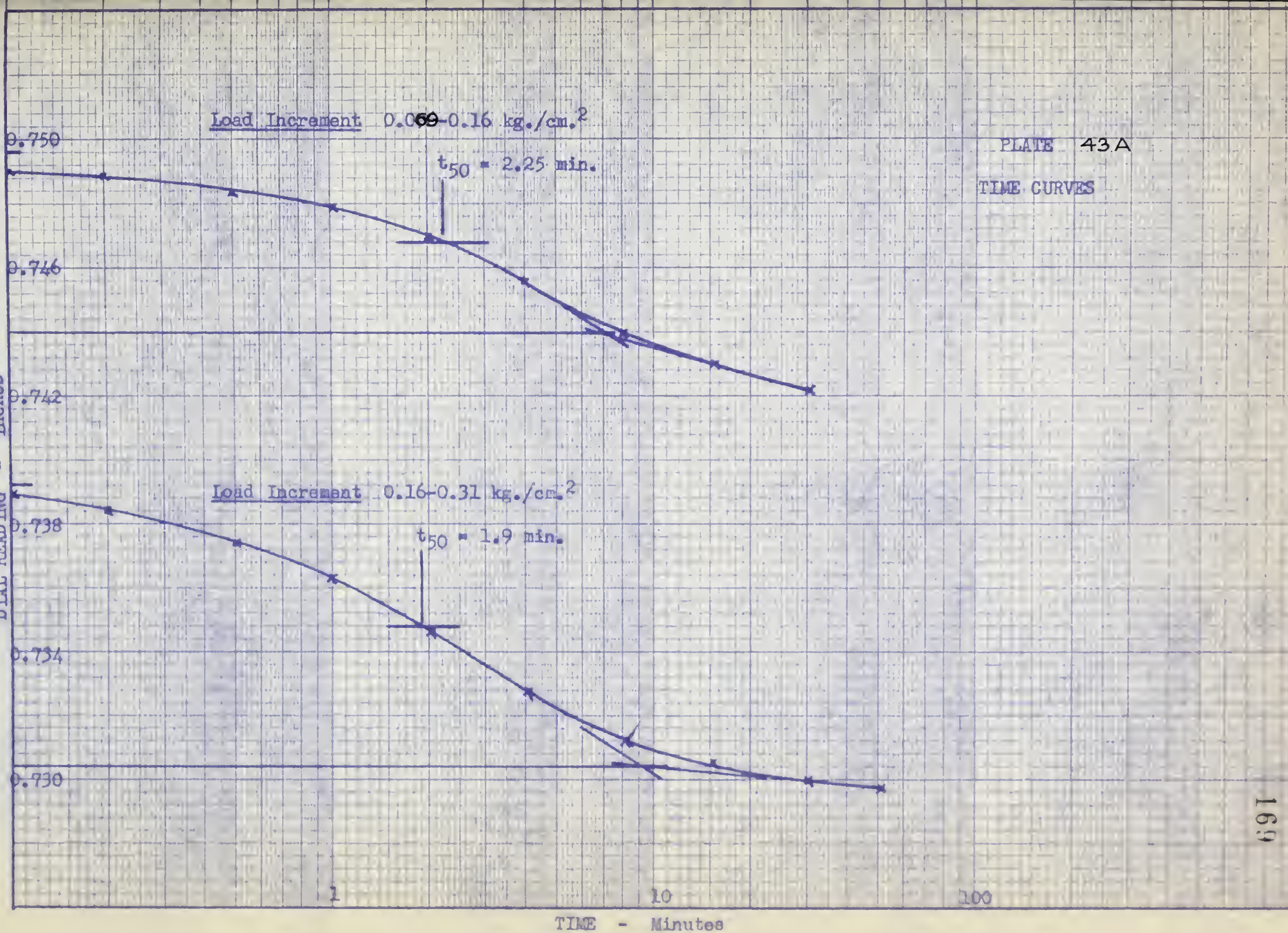
PLATE 43A
TIME CURVES
Load Increment 0.069-0.16 kg./cm.^{2}
t_{50} = 2.25 min.
Load Increment 0.16-0.31 kg./cm.^{2}
t_{50} = 1.9 min.
0.750
0.746
0.742
0.738
0.734
0.730
1
10
100
DIAL READING - Inches
TIME - Minutes

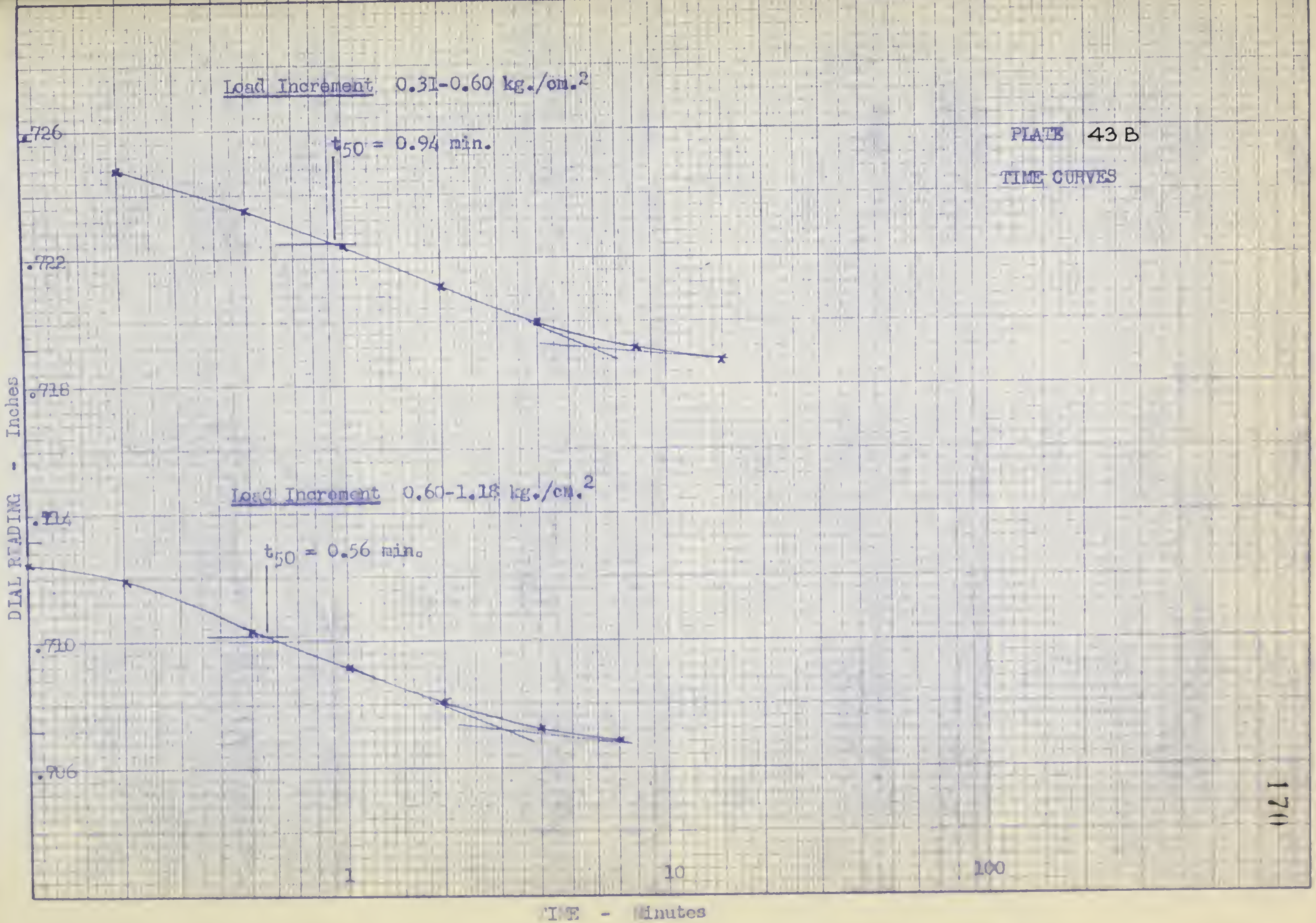
PLATE 43 B
TIME CURVES
Load Increment 0.31-0.60 kg./cm.2
t50 = 0.94 min.
Load Increment 0.60-1.18 kg./cm.2
t50 = 0.56 min.
.726
.722
.718
.714
.710
.706
DIAL READING - Inches
1
10
100
TIME - Minutes

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CONSOLIDATION RESULTS

PROJECT	171
SITE	
SAMPLE	Silt
LOCATION	
HOLE	DEPTH
TECHNICIAN	DATE

Specific Gravity of Soil Solids G_s = 2.70 Height of Soil Solids H_s = 0.613 ins

Void Ratio e (End) = 0.537

Void Ratio e (Start) = 0.608

Void Ratio e (Start Dimensions) =

$e(End) = W\%(End) \times G_s$ $H_s = \left(\frac{Wt \cdot Soil}{G_s \times Area \times 2.54}\right)$ ins. e = previous $e \pm \frac{Def'l.}{H_s}$

Time Interval	Load on Pan (gms)	Corr. Dial Reading (ins.)	Deflection (ins.)	Deflection / H_s	Void Ratio e	Pressure Kg/cm² = T/ft²
1060m	20	.7513	.0434	+ .071	0.608	0.069
30m	50	.7422	.0343	+ .056	0.593	0.16
50m	100	.7298	.0219	+ .036	0.573	0.31
15m	200	.7188	.0109	+ .018	0.555	0.60
8m	400	.7069	.0010	∕ .002	0.535	1.18
4m	100	.7084	.0005	+ .001	0.538	0.31
8m	20	.7120	.0041	+ .007	0.544	0.069
6m	50	.7111	.0032	+ .005	0.542	0.16
4m	100	.7099	.0020	+ .003	0.540	0.31
9m	200	.7080	.0001	0	0.537	0.60
142m	400	.7039	.0040	∕ .007	0.530	1.18
110m	20	.7106	.0027	+ .004	0.541	0.069
15m	100	.7076	.0003	0	0.537	0.31

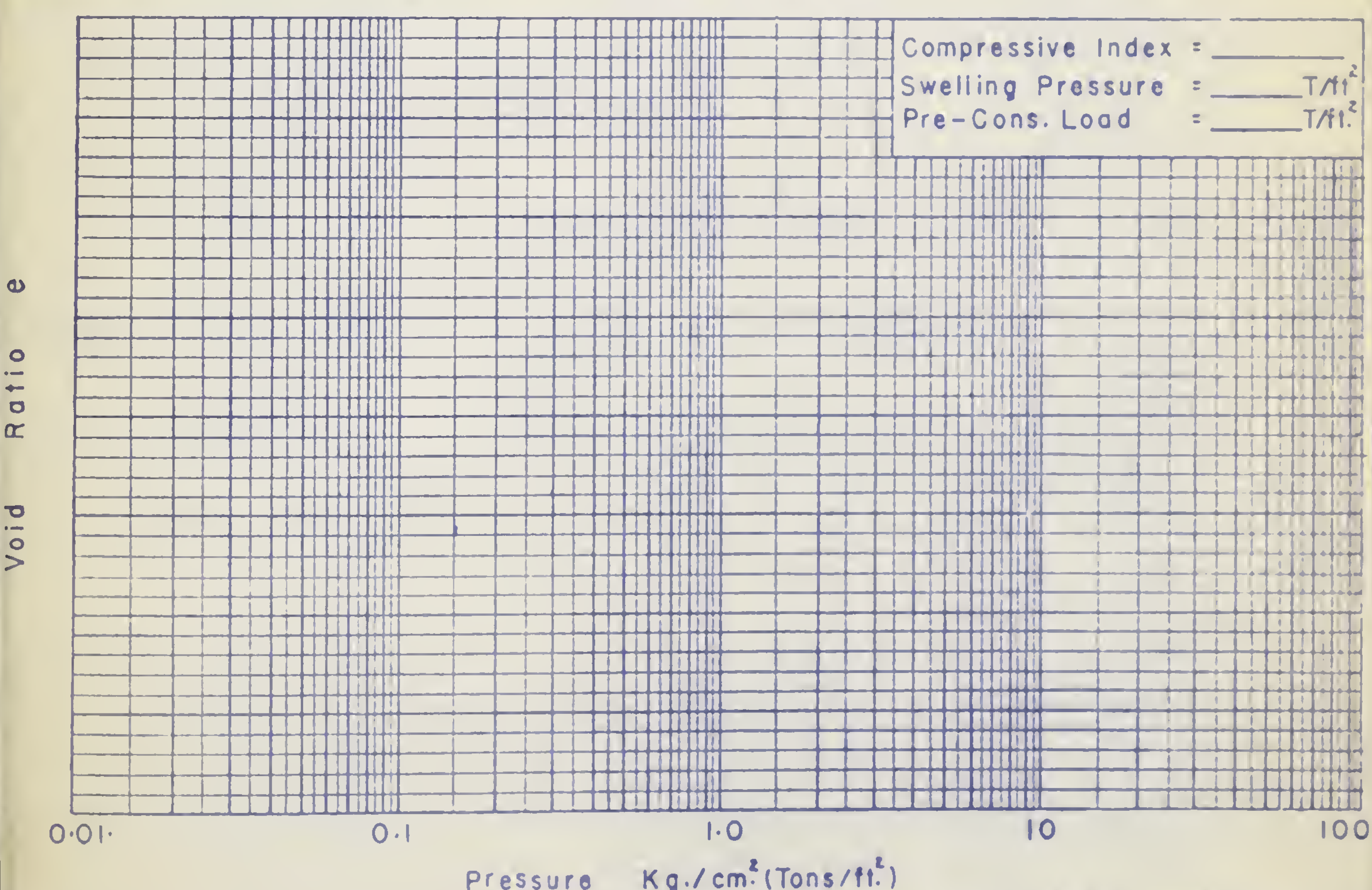

PLATE 44

UNIVERSITY of ALBERTA
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SOIL MECHANICS LABORATORY

CONSOLIDATION RESULTS

PROJECT	172
SITE	
SAMPLE	
LOCATION	
HOLE	DEPTH
TECHNICIAN	DATE

Specific Gravity of Soil Solids G_s = ________ Height of Soil Solids H_s = ________ ins

Void Ratio e (End) = ________

Void Ratio e(Start) = ________

Void Ratio e (Start Dimensions) = ________

$e(End) = W\%(End) \times G_s$ $H_s = \left(\frac{Wt \cdot Soil}{G_s \times Area \times 2.54}\right)$ ins. e = previous $e \pm \frac{Def'l.}{H_s}$

Time Interval	Load on Pan (gms)	Corr. Dial Reading (ins)	Deflection (ins.)	$\frac{Deflection}{H_s}$	Void Ratio e	Pressure $Kg/cm^2 = T/ft^2$
9m	200	.7059	.0020	- .003	0.534	0.60
15m	400	.7028	.0051	- .008	0.529	1.18
32m	20	.7079	0	0	0.537	0.069

Compressive Index = 0.066

Swelling Pressure = NIL T/ft²

Pre-Cons. Load = NIL T/ft²

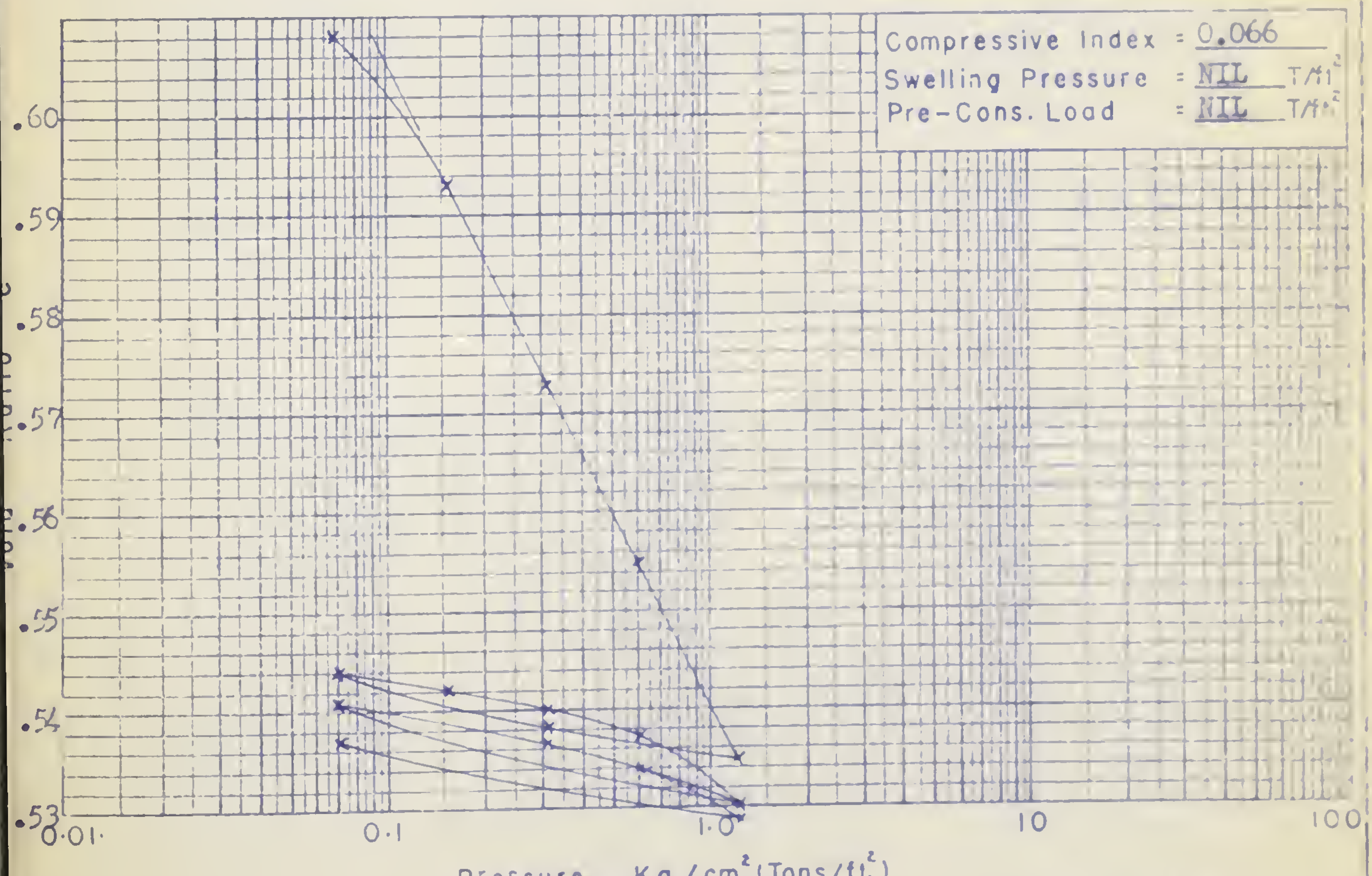

PLATE 44

TABLE XV

CALCULATIONS ON CONSOLIDATION RESULTS

INCREMENT kg./cm.2 (1)	t_{50} sec. (2)	2H in. (3)	H^2 cm.^{2} (4)	c_v cm.^{2}/sec. (5)	a_v cm.^{2}/gm. (6)	e (7)	k cm./sec. (8)
0.069-0.16	135	1.01	1.64	0.0024	0.00016	0.60	2.4×10^{-7}
0.16 -0.31	110	1.00	1.61	0.0029	0.00013	0.58	2.4 x "
0.31 -0.60	56	0.99	1.58	0.0056	0.000062	0.56	2.2 x "
0.60 -1.18	34	0.98	1.54	0.0091	0.000034	0.54	2.0 x "

The following notes apply to the above table:

1. The t_{50} values were obtained from the time curves which are included in this Appendix.

2. 2H is the average thickness of the sample for the loading increment under consideration.

3. The value of c_v (the coefficient of consolidation), was determined using the equation,

$$c_v = \frac{TH^2}{t}$$

where T is the time factor and is equal to 0.2 for 50% consolidation and the drainage conditions of the test performed. (See The Fundamentals of Soil Mechanics by Donald W. Taylor, fifth printing, September 1951, chapter 10).

4. The value of a_v (the coefficient of compressibility) was determined using the equation

$$a_v = e_1 - e_2/p2 - p1$$

where e and p refer to void ratios and applied unit loads, respectively.

5. The permeability (k) was computed using the equation

$$k = \frac{c_v \; a_v \quad w}{1 + e}$$

All values used in the equation are the average for the increment considered.

TABLE XVI

CAPILLARITY TEST DATA

DATE	TIME	HG. ELEV. Left Cm.	Right Cm.	DIFF. (3)-(4) Cm.	DIFF. (5)13.6	HEIGHT OF WATER COLUMN Cm.	NEGATIVE PRESSURE Cm of H_2O
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Elevation of bottom of specimen was 135.5 Cm.							
Sept. 17	1650	55.0	52.7	2.3	31	80	111
Sept. 18	840	55.5	52.2	3.3	45	80	125
"	930	55.8	52.0	3.8	52	80	132
"	1055	56.2	51.6	4.6	63	79	142
"	1150	56.4	51.3	5.1	69	79	148
"	1355	56.7	51.1	5.6	76	79	155
"	1540	57.1	50.6	6.5	88	78	166
"	1630	57.4	50.3	7.1	97	"	175
19	1900	57.5	50.3	7.2	98	"	176
"	1000	58.1	49.6	8.5	115	77	192
"	1100	58.5	49.2	9.3	126	"	203
"	1200	59.0	48.7	10.3	140	"	217
"	1330	59.4	48.3	11.1	151	76	227
"	1400	59.8	47.8	12.0	163	75	238
"	1500	60.3	47.4	12.9	176	"	251
"	1540	60.7	47.0	13.7	187	"	262
"	1615	61.2	46.6	14.6	199	74	273
"	1705	61.6	46.2	15.4	210	"	284
Sept. 20	905	62.0	45.8	16.2	220	"	294
"	945	62.4	45.4	17.0	232	73	305
"	1110	62.7	45.0	17.7	241	"	314
"	1310	63.5	44.2	19.3	262	"	334
"	1600	63.9	43.8	20.1	274	"	346
Sept. 23	900	64.1	43.6	20.5	279	71	350
"	945	64.5	43.2	21.3	290	"	361
"	1040	65.0	42.8	22.2	302	"	373
"	1245	65.4	42.4	23.0	313	70	383
"	1540	65.7	42.1	23.6	321	"	391
"	1630	65.9	41.8	24.1	328	"	399
"	2015	66.2	41.5	24.7	338	69	407
Sept. 24	840	69.6	38.0	31.6	430	66	496
"	1505	71.3	36.5	34.8	473	64	537
"	1630	72.4	35.5	36.9	502	63	565
Sept. 25	830	72.8	35.0	37.8	514	62	576
"	1050	73.4	34.5	38.9	530	"	592
"	1230	74.0	34.0	40.0	544	61	605

NOTE: Pressures were applied by means of a water-over-mercury U-tube. Column (3) applies to the water-mercury interface and column (4) to the mercury surface that is open to the atmosphere. The distance from the water-mercury interface to the bottom of the specimen is given in column (7).

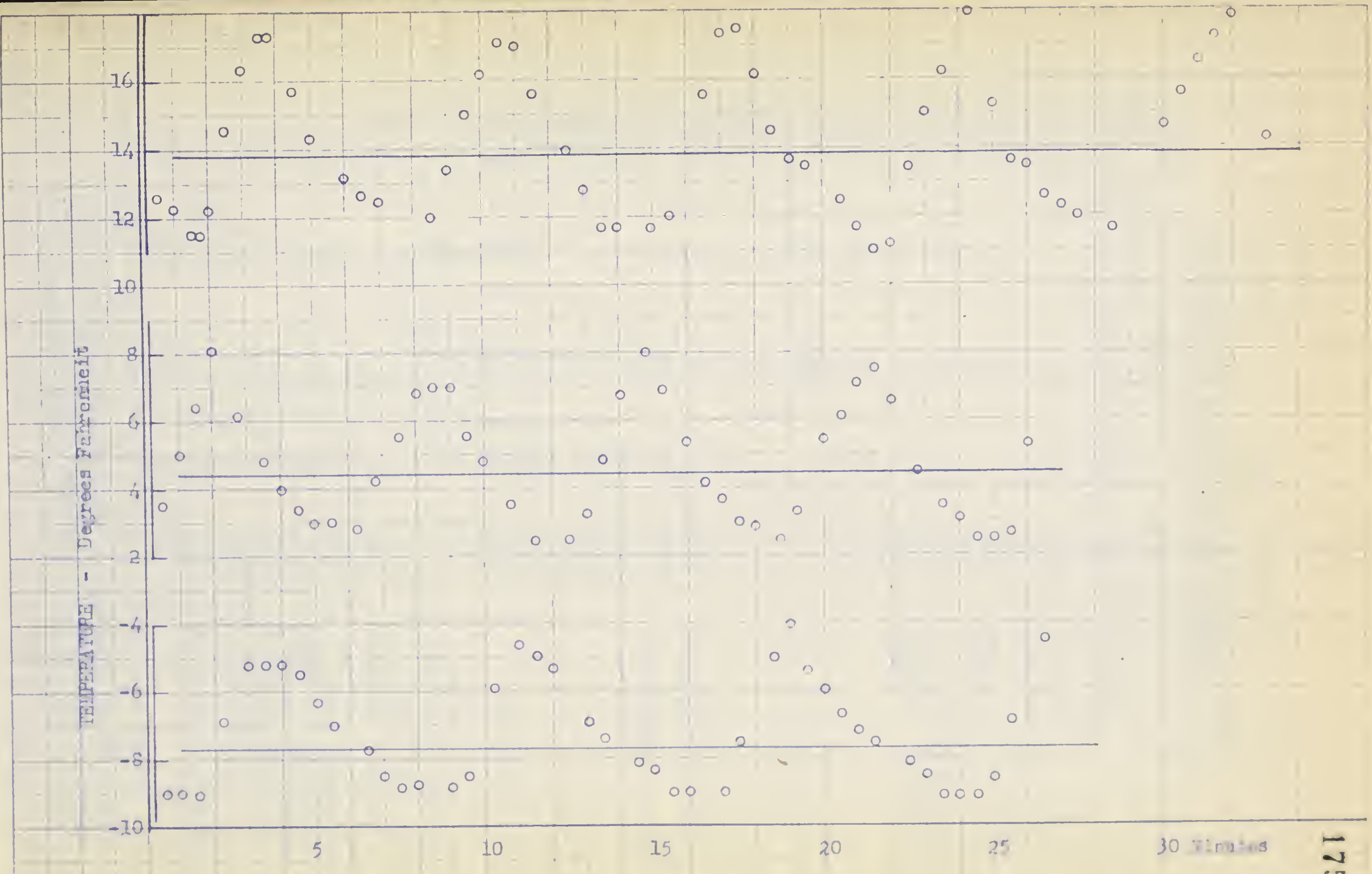

PLATE 45

COLD ROOM TEMPERATURE VARIATIONS UNDER THERMOSTAT CONTROL

TABLE XVII

DETERMINATION OF MEAN AND MEDIAN TEMPERATURES
FOR VARIOUS THERMOSTAT SETTINGS

Temp. °F (1)	Frequency (2)	(1)x(2) (3)	Greater Than No. (4)	Greater Than % (5)	
-4.25"	1	4	1	1.2	
-4.75	4	19	5	6.0	Mean Temp. = -7.6°F
-5.25	7	37	12	14.5	
-5.75	5	29	17	20.5	Median Temp. = -7.5°F
-6.25	5	37	22	26.5	
-6.75	8	54	30	36.2	The median is the
-7.25	8	58	38	45.8	quantity, "50% greater
-7.75	7	52	45	54.2	than".
-8.25	9	74	54	65.1	
-8.75	8	70	62	74.7	
-9.25	21	194	83	100	
	83	628			
+17.75					
+17.75	2	35	2	2.1	
17.25	7	121	9	9.4	
16.75	3	50	12	12.5	
16.25	6	97	18	18.7	Mean Temp. = +13.8°F
15.75	7	108	25	26.0	
15.25	5	76	30	31.3	Median Temp. = +13.8°F
14.75	6	86	36	37.5	
14.25	3	43	39	40.6	
13.75	9	124	48	50.0	
13.25	9	119	57	59.4	
12.75	8	102	65	67.7	
12.25	12	147	77	80.2	
11.75	15	177	92	95.8	
+11.25	4	45	96	100	
	96	1330			
+7.75	3	23	3	3.8	
7.25	5	36	8	10.0	Mean Temp. = +4.5°F
6.75	6	40	14	17.5	
6.25	6	37	20	25.0	The mean temp-
5.75	5	29	25	31.2	erature is the total
5.25	4	21	29	36.2	of column (3) divided
4.75	5	24	34	42.5	by the total of
4.25	6	25	40	50.0	column (2).
3.75	8	30	48	60.0	
3.25	10	32	58	72.5	Median Temp. = +4.3°F
2.75	22	59	80	100	
	80	356			

"The temperature given is that at the middle of the range covered. i.e. 4.25 indicates that the reading fell in the range 4.0 - 4.5 degrees Fahrenheit.

TABLE XVIII

THERMOCOUPLE RECORDER CALIBRATION

THERMOCOUPLE No. (1)	TEMPERATURE Trial 1 (2)	Trial 2 (3)
5	32.5	32.5
6	32.5	32.4
7	32.5	32.5
8	32.5	32.4
9	32.5	32.4
10	32.5	32.4
11	32.5	32.4
12	32.5	32.4
13	32.5	32.4
15	32.8	32.6
16	32.5	32.5

Note: The calibration was performed with the thermocouples immersed in a mixture containing approximately equal parts of ice and water.

A LATER CALIBRATION

Thermocouple No.	Temperature
1	33.2
2	"
3	"
4	"
5	"
6	33.3
7	"
8	"
9	"
10	"
11	"
12	"
13	"
14	33.2
15	"
16	"

TABLE XIX

CALIBRATION OF CAPILLARY SECTIONS

MANOMETER	ELEVATION Capillary cm.	ELEVATION Reservoir cm.	DEPRESSION cm.
(1)	(2)	(3)	(4)
1	20.0	20.9	0.9
	30.0	30.8	0.8
	40.0	40.8	0.8
	50.0	50.8	0.8
	40.0	40.8	0.8
	30.0	30.6	0.6
	20.0	20.6	0.6
2	20.0	20.9	0.9
	30.0	30.9	0.9
	40.0	40.8	0.8
	50.0	50.9	0.9
	40.0	40.6	0.6
	30.0	30.6	0.6
	20.0	20.6	0.6
3	20.0	20.7	0.7
	30.0	30.8	0.8
	40.0	40.8	0.8
	50.0	50.9	0.9
	40.0	40.7	0.7
	30.0	30.6	0.6
	20.0	20.6	0.6

MANOMETER	ELEVATION Capillary cm.	ELEVATION Reservoir cm.	DEPRESSION cm.
(1)	(2)	(3)	(4)
4	10.0	10.9	0.9
	20.0	20.8	0.8
	30.0	30.8	0.8
	40.0	40.9	0.9
	50.0	50.9	0.9
	40.0	40.6	0.6
	30.0	30.6	0.6
	20.0	20.5	0.5
	10.0	10.5	0.5
5	12.0	12.8	0.8
	14.0	14.9	0.9
	16.0	16.8	0.8
	18.0	18.9	0.9
	20.0	20.8	0.8
	22.0	22.8	0.8
	24.0	24.8	0.8
	30.0	30.9	0.9
	40.0	40.9	0.9
	50.0	50.9	0.9
	40.0	40.8	0.8
	30.0	30.8	0.8
	20.0	20.7	0.7